The Effect of High Temperature and Aging on Water-Base Drilling Fluids

by

Mohammed Shahjahan Ali

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

PETROLEUM ENGINEERING

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This thesis, written by Mr. Mohammed Shahjahan Ali under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Petroleum Engineering.

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DEDICATION

To My Wife and Son

ACKNOWLEDGEMENT

Praise and gratitude be to the Almighty, the creator and sustainer of the universe, and peace be upon his prophet Muhammad. Acknowledgement is due to the King Fahd University of Petroleum and Minerals for supporting this thesis through the Petroleum Engineering Department.

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I owe my wife, an expression of gratitude for her patience, understanding and encouragement which made this work possible. Finally, I am thankful to my colleagues and friends who made my stay at the University a memorable and valuable experience.

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THESIS ABSTRACT

Full Name of Student : MOHAMMED SHAHJAHAN ALI

Title of Study : THE EFFECT OF HIGH TEMPERATURE AND AGING ON WATER-BASE DRILLING FLUIDS

Major Field : PETROLEUM ENGINEERING

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Drilling fluid property changes due to elevated temperature and aging time frequently cause problems in drilling deep wells. A laboratory investigation of the effect of high temperature ($490°F$) and long aging time (30 days) on water-base drilling fluid properties is made with Fann Model 70 HTHP Viscometer and Baroid Roller Oven.

The results show a decrease in viscosity, yield point and gel strength with the increase in temperature. Shear stress for a particular temperature increases with the increase in shear rate, but shear stress at a given shear rate decreases with the increase in temperature. Viscosity, yield point and gel strength at a given temperature increase with aging time and aging effects are diminishing with the increase in aging time. Shear stress at a given shear rate increases with aging time and aging effects decrease with the increase in aging time. Finally, the value of the exponent of power law index n is calculated and found to be always less than unity.

MASTER OF SCIENCE

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

ملخص بحث

اسم الطالب : محمد شاهد جهان علي
مسمى البحث : تأثير درجة الحرار العالية والمدة الزمنية على سوائل الجفر في القاعدة المائيه .

القسم : هندسة البترول
تاريخ منح الدرجه : يونيو ١٩٩٠ م

تتغير سوائل الحفر تبعا لارتفاع درجة الحرارة والمدة الزمنية مما يسبب المشاكل باستمرار فى حفر الأبار العميقة . وقد تم عمل بحث معملي لتأثير الحرارة العالية (٤٩٠ ف) والمدة الزمنية المطولة (٣٠ يوم) على خصائص سوائل الحفر فى القواعد المائيه ، باستعمال طريقة فان موديل ٧٠ (درجة حرارة عليا وضغط مرتفع) وطريقة بارويد رولر اوقن .

وبينت النتائج انخفاضا فى اللزوجة ونقطة التحمل مع زيادة الحرارة . والجهد فى درجة حرارة معينة يزداد مع ازدياد معدل الجهد ولكن قوة الجهد فى معدل جهد معين ينخفض مع ازدياد درجة الحرارة . واللزوجة ومعدل التحمل فى درجة حرارة معينة يزداد مع مرور الزمن . والجهد فى معدل جهد معين يزداد مع مرور الزمن ويقل عامل التأثير الزمنى مع ازدياد المدة الزمنيه . واخيرا فأن قيمة أسى القوة يتم احتسابها وتكون دائما أقل من الوحدة .

الماجستير فى العلوم
جامعة الملك فهد للبترول والمعادن
الظهران ـ المملكة العربية السعوديه

CHAPTER 1

Chapter 1

INTRODUCTION

Successful drilling of deep, hot wells critically depends on the Rheological properties of the drilling fluids designed for specific down hole conditions. Rheological properties of water-base drilling fluids under down hole condition may be very different from those measured at the surface conditions. Because, elevated temperature affects the drilling fluid properties [2,4,5,7,14,15,17,18]. An increase in temperature reduces the effectiveness of most drilling fluid additives that would maintain the rheological, fluid loss, and electro-chemical properties. Problems of elevated temperature is accelerated when high chemical contaminants, such as salt of sodium, calcium and magnesium are encountered [20]. Elevated temperature itself is considered as one of the drilling fluid contaminant which can not be treated with any additives [33].

Drilling fluids in the lower portion of the hole become excessively thick when it is not circulated. Prolonged heating may cause solidification of drilling fluids [1]. In the case of stuck pipe, circulation may continue for long time at elevated temperature and thus aging comes under consideration. Aging affects the rheology of drilling fluid along with temperature [1,3,6,8, 11,12,16,20,21,25] and investigation shows that the effect of dynamic aging is greater than static aging [20].

The main objective of this study was to investigate the effect of both high temperature and long aging time on the rheological properties of water-base drilling fluids. The objectives have been fulfilled by experimental means. The experimental method includes two different equipments, namely (a) Baroid Roller Oven, to roll the mud and to allow the chemical reaction taking place in the mud, and (b) Fann Model 70 HTHP Viscometer, to measure the rheological properties of drilling fluids at high temperatures. Aging time of 30 days and temperature of $490°F$ has been achieved during the test. Mud formulation consists of bentonite, attapulgite, sodium chloride, lime , gypsum and VSVA (vinylsulfonate/vinylamide) in fresh water (distilled water).

Results of this study are evaluated on the basis of effective viscosity, plastic viscosity, yield point, gel strength, shear stress - shear rate relationship and are shown as a function of temperature and aging time.

CHAPTER 2

Chapter 2

LITERATURE REVIEW

The effect of elevated bottom hole temperature on drilling fluid properties became quite evident in the late 1930's when the molecular dehydrated phosphate and polyphosphate-type deflocculants were used as standard thinners. These thinners undergo thermal degradation at temperatures of 150 to 200°F and are ineffective when the bore hole temperature exceeds these limits. Tannin compounds, primarily quebraco extract, were used as thinner in higher temperature wells in the 1940's, and these thinners were more stable than phosphate but their range of effectiveness were not satisfactory [13].

In 1952, **Gray et al.** [1] investigated the effect of temperature on lime-treated water-base mud and found that high temperature causes severe gelation or solidification of these muds for temperatures above 300°F. They concluded that (a) pressure does not significantly affect the consistency of mud stored at high temperature, (b) increase in temperature speeds up the hardening of lime-treated mud, and (c) aging and aging temperature decreases the alkalinity and penetration rate as shown in Figure 2.1.

Later in 1958, **Srini-vasan** [2] used a laboratory model Fann V-G meter to measure the viscosity, yield value and gel strength of clay water drilling mud at temperatures of 80, 120, 160 and 180°F, and found that plastic

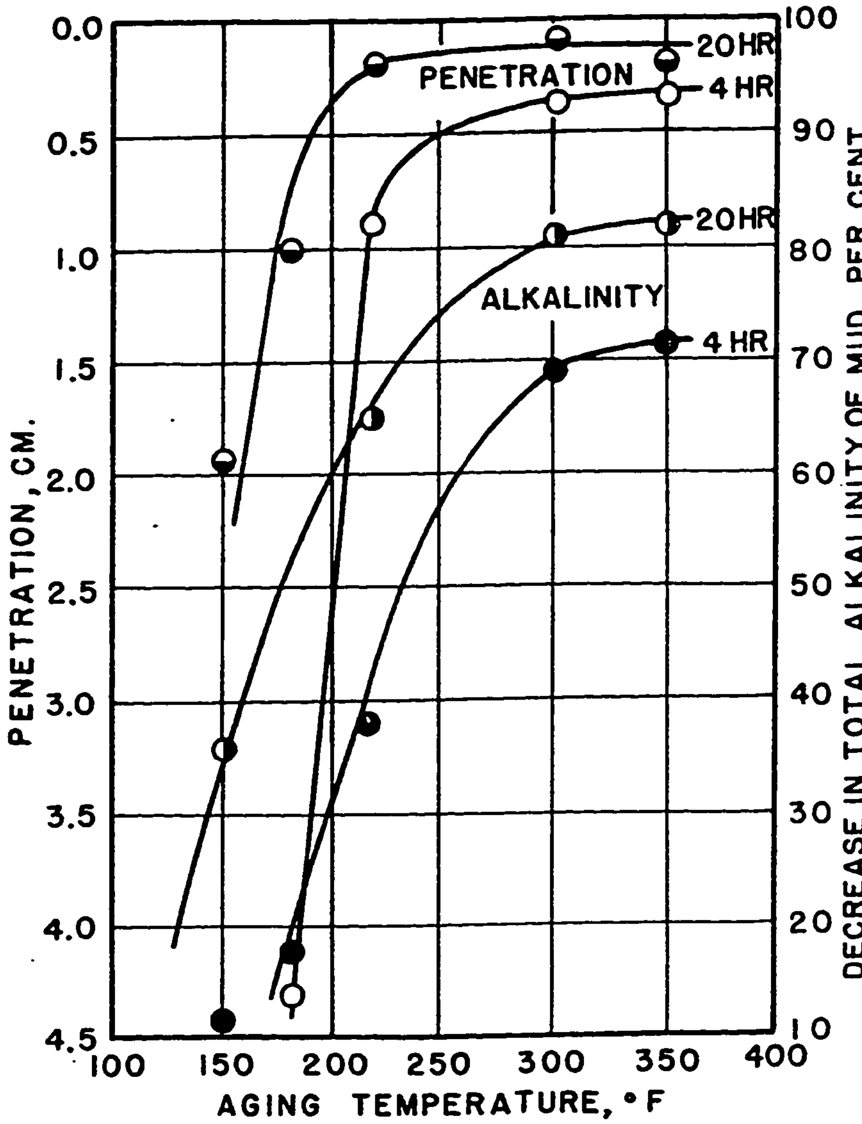


Fig.2.1: Changes in Alkalinity and Penetration Rate of Lime-Bentonite Mud with Aging Temperature [Ref. 1].

viscosity decreases with temperature and gel strength increases with increase in temperature. He also studied the effect of temperature on $\mu_{P_{mud}} / \mu_{water}$ ratio, where $\mu_{P_{mud}}$ is the plastic viscosity of mud and μ_{water} is the viscosity of water, and observed that it increases with the increase in temperature.

In 1959, **Cowan** [3] Performed experiments with lignite-sodium-surfactant mud at temperatures as high as $450°F$. The mud was static-aged for 16 hours , 64 hours and 352 hours at a temperature of $400°F$. He observed that the plastic viscosity decreased and shear strength increased with aging time, but the changes in other property were not that much.

In 1963, **Hiller** [4] studied the rheological properties on clay suspension and drilling fluid at high temperature and pressure. HPHT rheometer was used for the test. The maximum test temperature was $350°F$ and the test pressure was 8000 psi. The effect of temperature on shear stress-shear rate is shown in Figure 2.2. His study concluded that the flow properties of clay suspensions and of drilling fluids differ considerably under bottom hole conditions and the magnitude of these differences is not generally predictable. Certain generalizations concerning the effects of temperature and pressure on the flow behavior of drilling fluids are possible and these generalizations are based on the qualitative relationship that exists between rheological behavior and colloidal structure. The data obtained of this study can be applied in

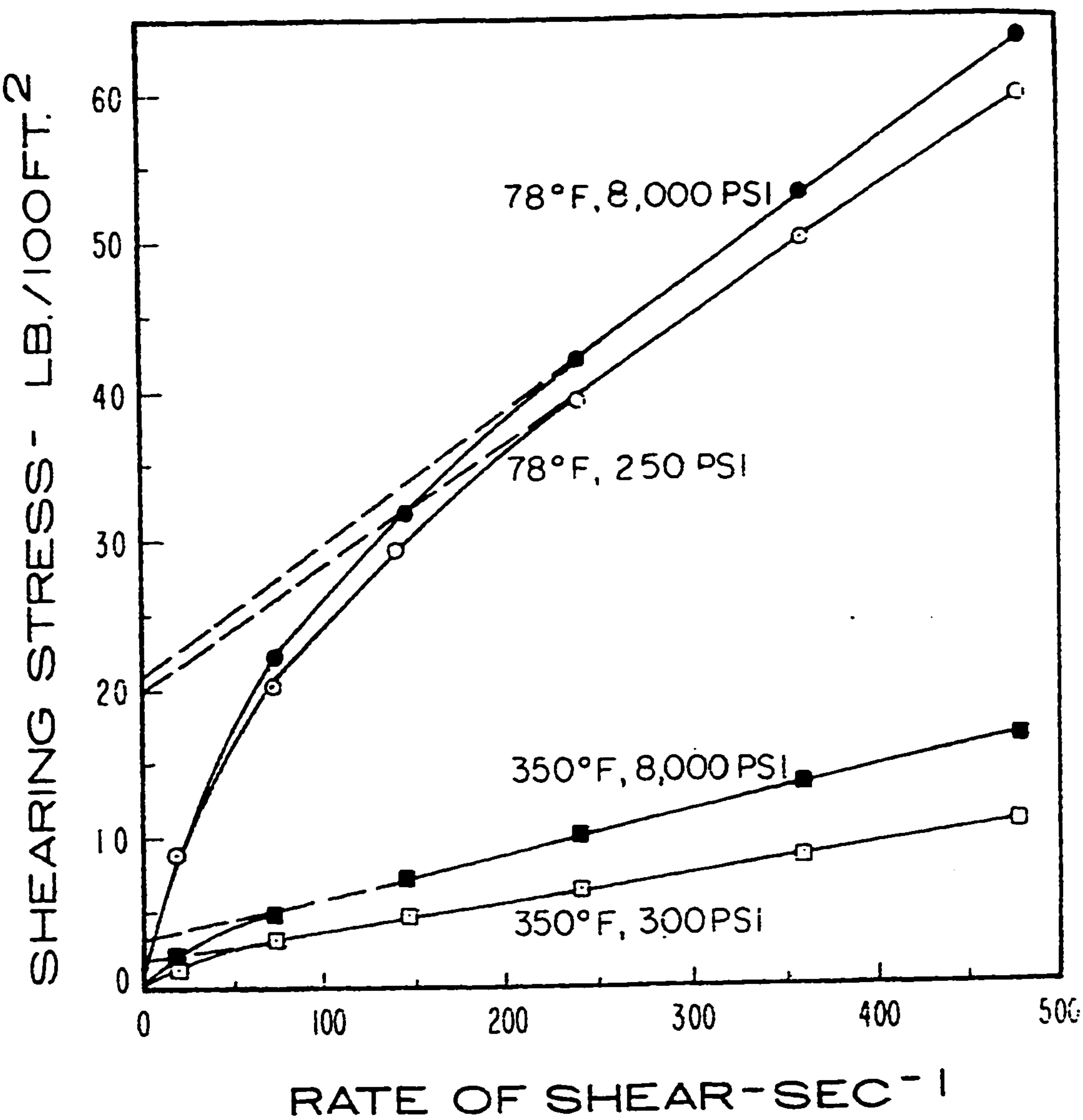


Fig.2.2: Shear Stress-Shear Rate Plot for a 4 Per Cent Pure Sodium Montmorillonite Suspension in which 5 meq./litre of NaOH is added [Ref. 4].

calculating start-up pressures after periods of interrupted circulation and in computing the suspending ability of the quiescent drilling fluid. Both of these characteristics are dependent on the static gel strength which has been found to vary considerably with temperature and pressure.

In the same year, **Weintritt and Hughes** [5] carried out experiments to study the drilling fluid properties at temperatures upto $500°F$ and found that at high temperatures, quartz, kaoline, or bentonite will affect one or more properties of a good - quality high temperature drilling fluid. The critical nature of these solids is more apparent in measurements of flow properties and shear strength than in filter loss.

Annis [6] in 1967 investigated the changes in rheological property with time and temperature up to $300°F$ by a concentric-cylinder, rotational viscometer of the Fann type. His experiments covered the effects of temperature and aging on shear rate - shear stress (Figure 2.3), gel strength, and viscosity. The study concluded that: (a) high temperature causes flocculation of bentonite clays, resulting in high yield points, high viscosities at low shear rates, high gel strengths and a permanent thickening of the mud, (b) proper treatment of bentonite mud with NaOH and lignosulfonate reduces the effect of dispersion and flocculation at high temperature.

In the same year, **Bartlett** [7] studied the effect of temperature on the

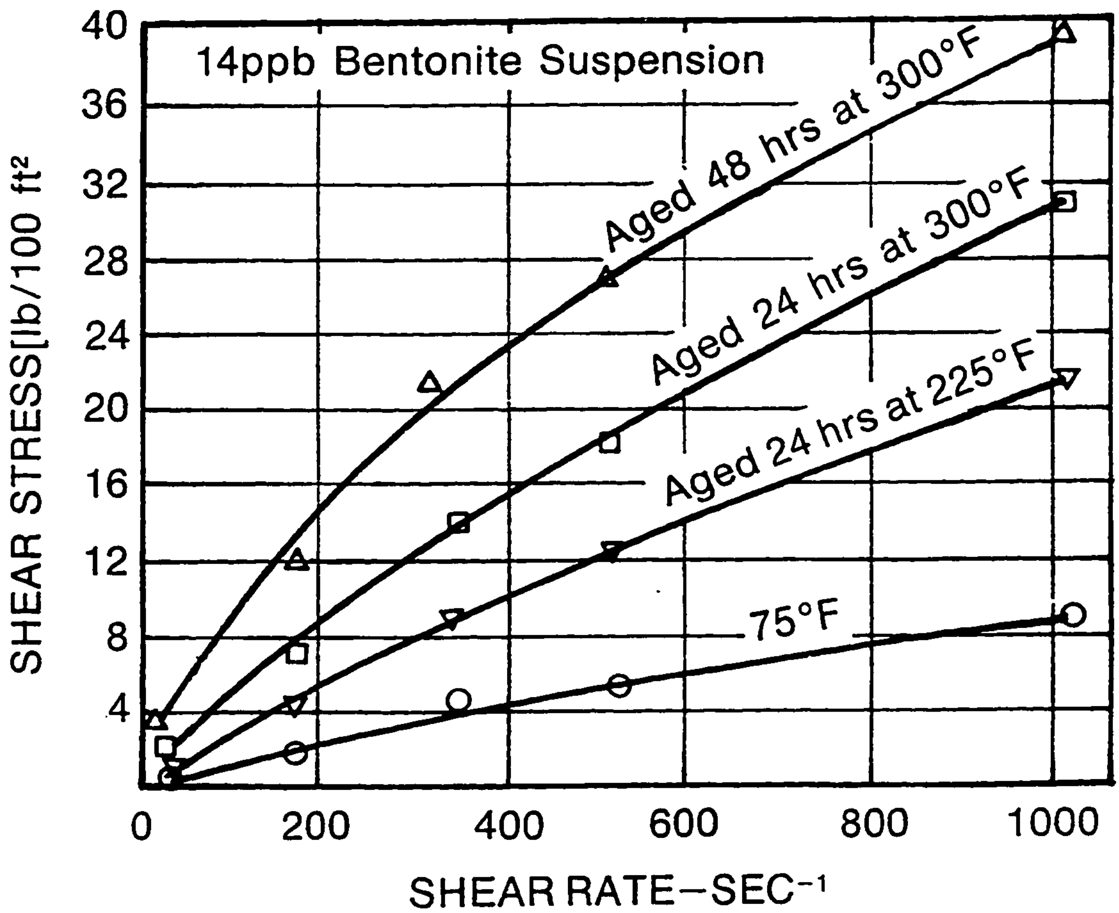


Fig.2.3: Effect of Hot Rolling on Shear Stress-Shear Rate Relationship [Ref.6].

flow properties of drilling fluids and found a drastic difference in viscosity at various temperatures. He studied the behaviour of lignosulfonate mud at temperatures upto 320°F and drew the following conclusions: (a) drilling fluids do not behave as Bingham plastics, (b) data obtained at surface temperatures can not be used to determine flow conditions at higher temperatures encountered in the well, (c) with respect to lignosulfonate muds, a gelling effect occurs at high temperatures when the mud flows with shear rate in the range of 0 to 250/sec.

Later in 1972, **Branscum** [8] found that aging time (16 hrs. hot rolling) and aging temperature (176°F) increases the plastic viscosity and decreases the yield point and water loss of a CMC polymer mud.

In the year of 1974, **De Lautrec** [9] studied the dynamic properties of the drilling fluids to simulate the severity of bore-hole condition (pressure: 7250 psi, temperature: 482°F, circulation speed of fluid: 13.12 ft/sec). His study included the evaluation of rheological and filtration characteristics of drilling fluids, choice of most suitable fluids for eliminating plugging caused by mud.

Wayant [10] in 1975 carried out experiments with the Magcober high temperature (Maximum temperature: 400°F) mud stabilization system as shown in Figure 2.4. His study shows that the mud stabilization system is an effective system to stabilize mud within short periods of time. A bentonite

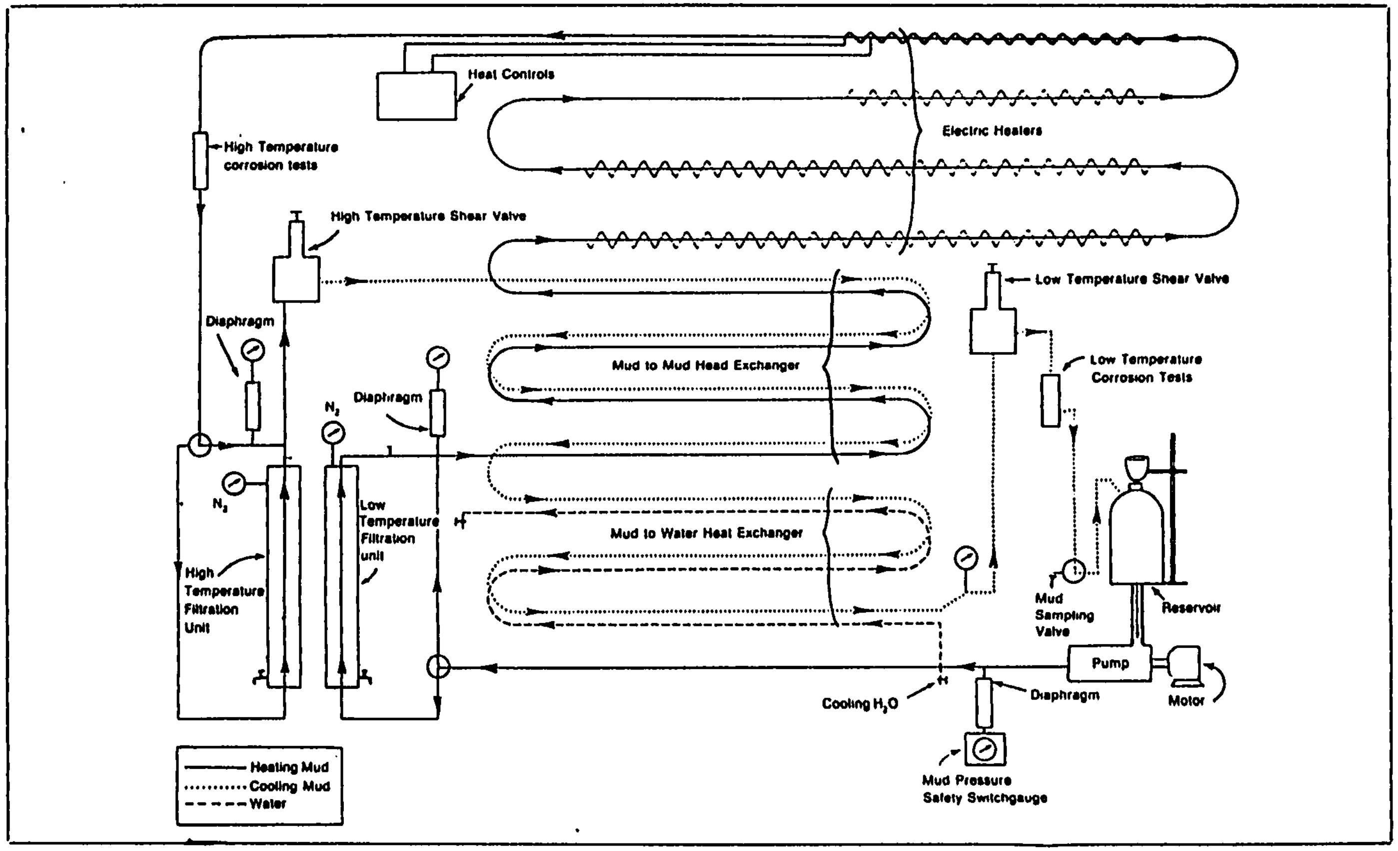


Fig.2.4: Magcobar High Temperature Mud Stabilization System [Ref.10].

slurry of 28 pounds of bentonite per barrel of water; 18.8 gal/hr mud flow rate; 180°*F* initial cycle temperature; moderate shear of 80 - 100 psi across shear valve and with pH value between 9.2 - 9.5 was stabilized within 15 hours. Subsequently, when an intense shear of 300 psi was applied across the valve for 90 minutes with the temperature remaining at 180°*F*, no change was noted. When cycle temperature was raised to 300°*F*, the flow properties changed and the mud again reach stability within 28 hours and thus the mud was stabilized effectively at two temperatures in slightly more than one day. Moreover, the atmospheric reservoir of the system makes it easy to treat and test the mud so that it can be kept in correct chemical balance during circulation periods.

In the next year, **Carney and Meyer** [11] studied the effect of high temperature on sepiolite using as clay minerals with fresh water. They found that clay minerals from Amargosa Desert in Nevada were extremely temperature stable. Slurry of sepiolite were studied using a Fann Model 50 viscometer at temperatures ranging from room temperature to 500°*F*. It was noted that a fairly constant viscosity was exhibited by various sepiolite slurries over the entire temperature range. A specially designed ultra high temperature, high pressure thickening time tester was used for temperatures upto 750°*F*. The slurry was static aged for 24 hours at 750°*F* and observed that apparent viscosity, plastic viscosity, yield point were higher than initial values, but the gel strengths were lower after 24 hours aging.

In 1978, **Bannerman and Neal** [12] performed a study with sepiolite clay instead of bentonite and found that sepiolite based drilling fluid offered distinct advantages in geothermal zones, including high temperature stability, ease of rheological control, reduction in lost circulation and mud cost (5 - 10%). The most successful system tested was composed of 16 lb/bbl of sepiolite, 5 lb/bbl of modified lignite, 2 lb/bbl of sodium polyacrylate, 1 lb/bbl caustic soda and the mud was aged for 16 hours at $460°F$.

In the year of 1980, **Chesser** [13] found from laboratory and field tests that bentonite mud treated with sodium salt of sulfonated styrene maleic anhydrite (SSMA) exhibit excellent stability at a temperature of $500°F$ and pressure of 15,000 psi (Figure 2.5). Aging effect was not considered in his test.

Thomas [14] in 1982 used starch and CMC(carboxy methyl cellulose) as fluid loss control agent, but found that their use is limited to temperatures of $225°F$ and $200°F$ respectively.

In 1984, **Son et al.** [15] studied the rheology and filtration property of VSVA (vinylsulfonate/vinylamide) mud and compared the results with PHPA (partially hydrated polyacrylamide) mud and observed that VSVA is a more

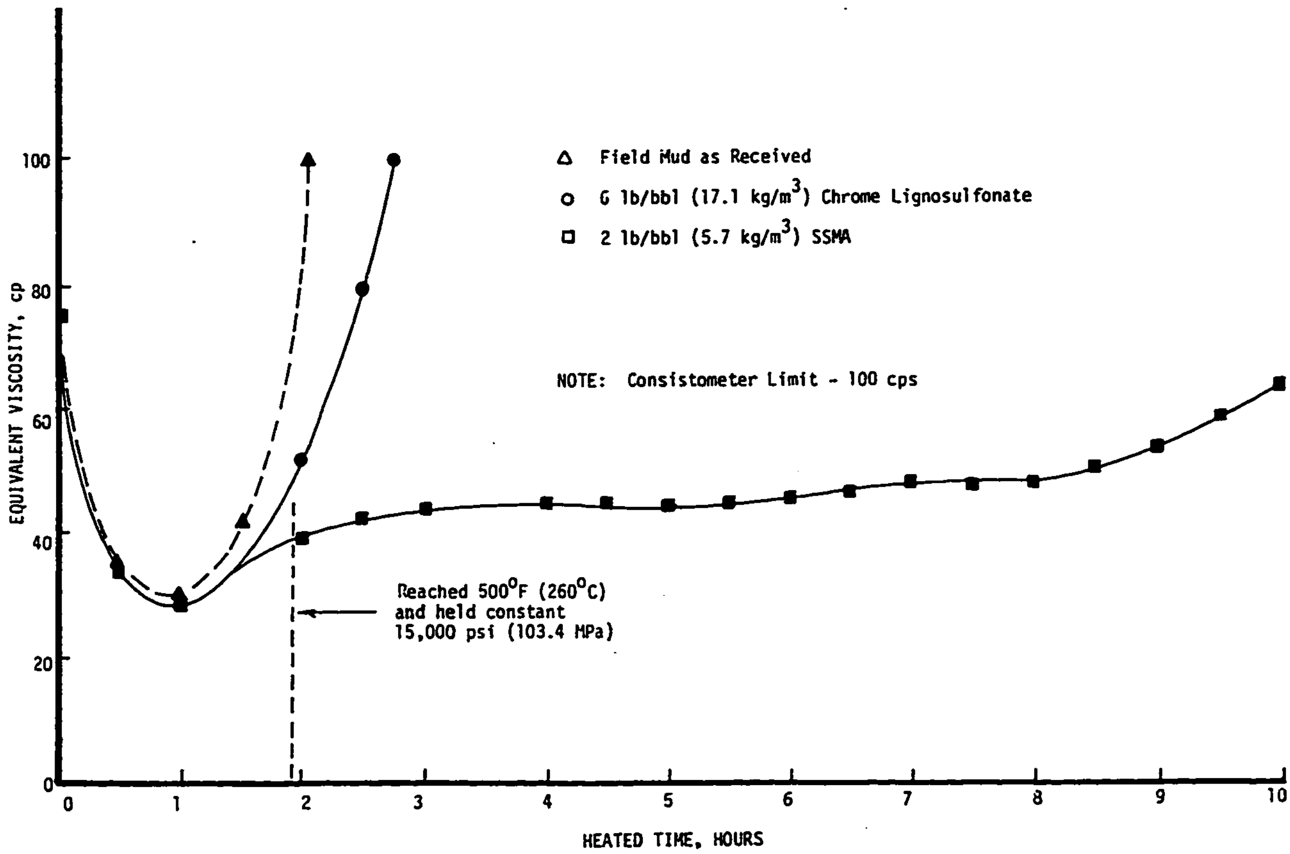


Fig.2.5: Effect of Heat on SSMA Stability [Ref.13].

rheology stabilizer than PHPA at temperatures above 400°F. The study included the static aging of the mud for 24 hours and concluded that (a) VSVA allows use of water base drilling fluids to temperatures in excess of 400°F, (b) VSVA synthetic polymer is an effective fluid loss reducers and rheology stabilizer at 400°F, and in the presence of high electrolyte, (c) VSVA promotes high tolerance to solids and cement contamination in nondispersed water-based muds. (d) VSVA promotes savings in drilling cost through low initial treatment and maintenance level.

Clements et al. [16] in 1985 studied the rheological properties of lignosulfonate mud and found that the mud has stable rheological properties even above 450°F after 16 hours of static aging. The mud has also good tolerance of electrolyte concentrations.

In the same year, **Block** [17] studied the effect of temperature on rheology of a clay free alumina gel drilling fluid consisting of bulky anions of inorganic (sulfate) and organic (tartrate and citrate) materials. Compatible cross-linked poly vinyl alcohol was added for filtration control. The mud was tested at 350°F and found suitable. Laboratory measurements performed with a Haake RV3 rheometer and field tests were made with a Baroid multispeed rheometer.

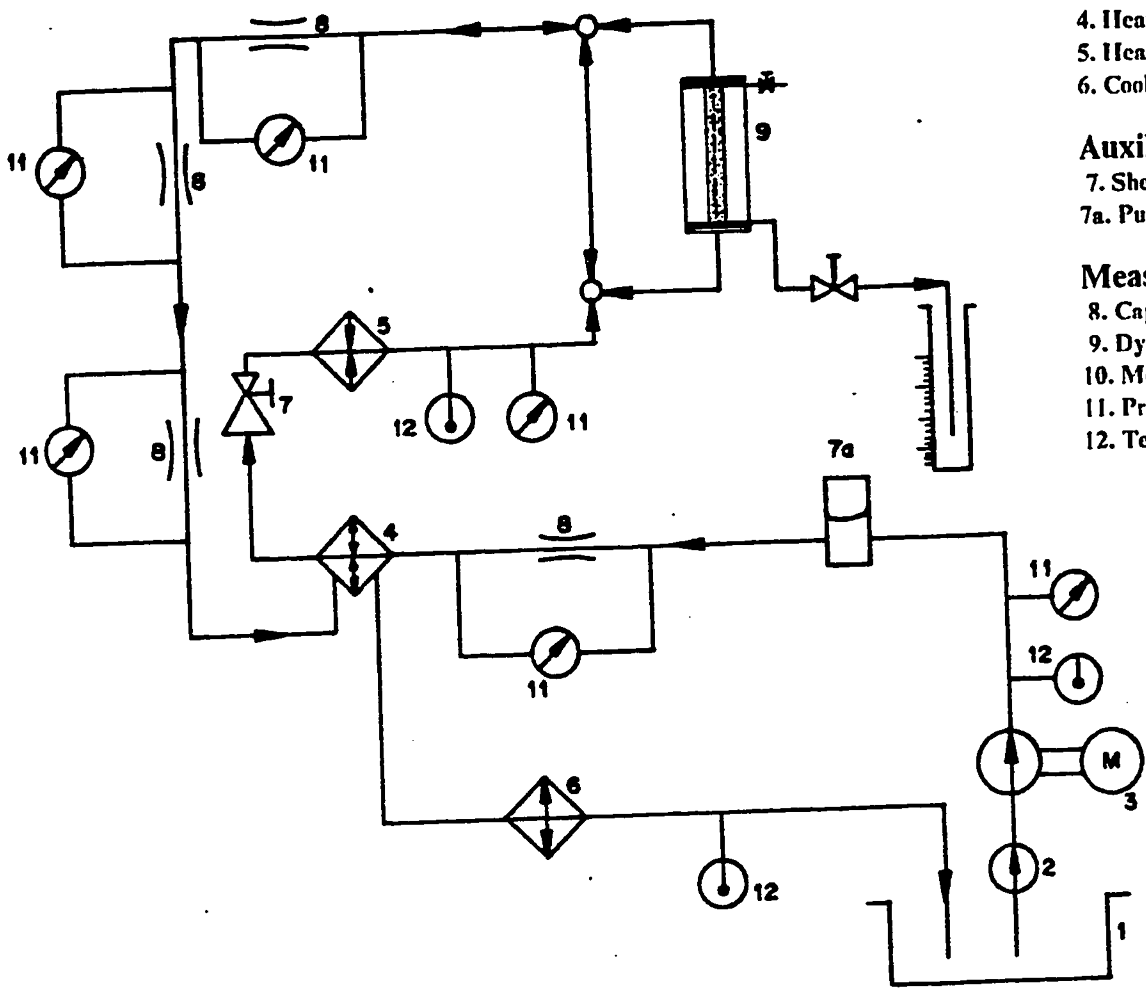
Later in the same year, **Hille** [18] found experimentally that VSVA (vinylsulfonate/vinylamide) copolymer muds are stable to temperature above $392°F$ with high electrolyte concentration (calcium and magnesium ion concentration). It reduces the filter loss even at high salt concentrations which minimizes formation damage and pipe sticking and also reduces the thermo-gelling of drilling fluid.

Perricone et al. [19] in 1986 studied the properties of two synthetic high molecular-weight vinyl sulfonate copolymers namely acrylamido methyl propane sulfonate (AMPS) and acrylamide (AM) and their use in water-base mud for controlling high temperature filtration properties. Vinyl sulfonate copolymers were shown to exhibit thermal stability because they are not depolymerized by the hydrolytic and oxidative environments of the drilling mud and they do not form insoluble salt in the presence of electrolyte. These copolymers are effective for filtration control for water-base muds over a wide range of electrolyte concentrations and remain effective after dynamic aging (16 hours) at $350°F$.

In 1987, **Adelina et al.** [20] Studied the effect of temperature on a clay free salt water mud treated with synthetic VSVA (vinylsulfonate/vinylamide) polymers. The rheology and API filtration loss properties were observed after 16 hours of heat treatment(hot rolling at $150°F$ and static aging at 250, 300 and 400°F under 300 psi pressure). Their results show that plastic viscosity, yield point, gel strength and API filtrate were greater in hot rolling than static aging. They also found that pH increases with temperature. They concluded that VSVA polymer can be used in water-base mud above 400°F and it is a good fluid loss reducer.

In the same year, **Al-Marhoun and Rahman** [21] used laboratory test procedures to simulate the bottom hole conditions. They used a dynamic flow loop as shown in Figure 2.6. HPHT viscometer, HPHT filter press, roller oven and other API standard equipment were also used in this study. The mud was aged for 24 hours in the roller oven. They studied the effect of temperature (up to 347°F) on viscosity, filtration loss and corrosion rate and observed that viscosity under the roller oven conditions increases up to a temperature of 248°F and then decreases, but viscosity in the HPHT viscometer decreases with temperature. Yield point decreases with temperature. Filter loss increases with temperature.

In 1988, **Fisk and Jamison** [22] studied the physical properties of drilling fluids at temperatures 184°F and pressures (20,305 psi). They used mineral oil, diesel oil and water as three base fluids and their investigation concluded that (a) rheological properties of oil base fluids fit a logarithmic temperature prediction equation while, water base fluids are characterized by linear



Pump Section
1. Mud Tank
2. Charge Pump
3. Mud Pump

Heating Section
4. Heat Exchanger
5. Heater
6. Cooler

Auxilliaries
7. Shear Valve
7a. Pulse Damper

Measuring System
8. Capillary Viscometer
9. Dynamic Filtration Cell
10. Measuring Cylinder
11. Pressure Gauge
12. Temperature Gauge

Fig.2.6: Dynamic Flow Loop [Ref.21].

viscosity as a function of temperature, (b) system pressure had negligible effect on dynamic filtration rates, (c) for differential pressures greater than 109 psi, no change in filtration rates of clay based fluids was observed for a set of constant test parameters, indicating that both water and oil base drilling fluids form highly compressible filter cakes, (d) thermal induced flocculation of the water base fluid additives increased filtration rate, yield point, and decreased filter cake compressibility. This effect was not observed in oil base fluids.

In the same year, **Alderman et al.** [23] carried out experiments with water-base muds to study rheology at temperatures up to $266°F$ and pressures up to 14500 psi. They concluded that high shear viscosity decreases with increasing temperature in a similar manner for all drilling fluids examined and increases with pressure to an extent which depends on mud density. Yield stress is essentially independent of pressure and weakly dependent on temperature. Their study did not simulate the bottom-hole conditions and did not consider the aging effect.

Later in the same year, **Al-Marhoun and Rahman** [24] performed experiments to evaluate the drilling fluid system under simulated bottom hole conditions for penetrating formation with electrolyte influx. They used different composition of drilling fluid to establish the thermal and chemical stability of the mud on the basis of rheological, filtration rate (static and dynamic) and electrochemical properties (pH value, corrosion rate). They reached a maximum temperature of 446°F and their study concluded that synthetic copolymers(VSVA/SSMA) are proved to be most effective additives for the stability of water-base drilling fluids under severe bottom hole conditions and partial substitution of bentonite by attapulgite improved the performance of drilling fluid.

Also in 1988, **Elson et al.** [25] studied the application of a lime- based drilling fluid in high-temperature, high-pressure environment. A few lime muds were used above 300°F, especially when weighted to 18.5 lb/gal. The use of vinyl sulfonate/vinyl amide copolymer, low molecular weight polyacrylate terpolymer, grafted lignosulfonate and sulfonated asphalt provided stable fluids for temperatures upto 350°F. The mud was static aged for 16 hours at 350°F.

The summary of the literature review is presented in table 2.1 and it is observed from the summary that most of the investigations were done at static aging conditions. Dynamic aging is more important than static aging to simulate the actual drilling conditions and the effect of dynamic aging is greater than static aging [20]. Only few investigations [6,8,12,20,21] were made to study the effect of both temperature and dynamic aging on water-base drilling fluid properties. The maximum temperature and dynamic aging

Table 2.1: Summary of Literature Review

Investigator & year	Study		Remarks
	System	Parameters	
Gray et al. (1952)	Lime Mud	- Temperature - Pressure - Static Aging	- Gelation or solidification of mud - Insufficient effect of pressure - Decrease in alkalinity and penetration rate
Srini-Vasan (1958)	Clay-Water Mud	-Temperature 50° F - 180° F	- PV increases, and GS decreases - Viscosity ratio increases
Cowan (1959)	Lignite-Sodium Surfactant Mud	-Temp., 450° F -Static Aging, 16, 64, 352 hrs	- PV decreases, shear strength increases with aging time
Hiller (1963)	Clay Suspension & Drilling Fluid	-Temp., 350° F -Press., 8000 psi	- Shear stress decreases with shear rate for increase in temperature
Weintritt et al. (1965)	Water-base Mud (bentonite)	-Temp., 500° F	- Quartz, kaoline, or bentonite affect the drilling fluid properties
Annis (1967)	Water-base Drilling Fluid (bentonite)	-Temp., 300° F -Dynamic Aging, (48 hrs.)	- High YS, GS and low viscosity at low shear rate - NaOH and ligno-sulfonate reduces dispersion and flocculation effect

*Temp. - Temperature

(Table 2.1 continued)

Bartlett (1967)	Ligno-sulfonate Mud	-Temp., 320° F	- Gelling effect at high temperature
Branscum (1972)	CMC Polymer Mud	-Temp., 176° F -Dynamic Aging, 16 hrs.	- PV increases with temperatures - YS, water loss decreases with aging time
De Lautrec (1974)	Water-base Mud (bentonite)	-Temp.,482° F -Press. 7250 psi	- Dynamic fluid loss is greater than static fluid loss
Wayant (1975)	Waterbase Mud (bentonite)	-Temp., 400° F	- Magcobar mud stabilization system is very effective to stabilize mud within short time
Carney & Meyer(1976)	Sepiolite Mud	-Temp., 750° F -Static aging, 24 hrs.	- Apparent viscosity, PV, YP were higher and G.S were lower after 24 hrs. aging
Bannerman & Neal(1978)	Sepiolite Clay Mud	-Temp., 460° F -Dynamic Aging, 16 hrs.	- High temperature stability of the mud - Easy of rheology control - Less water loss
Chesser (1980)	Low-Molecular Wt. Copolymer Mud	-Temp., 500° F -Press., 15000 psi	- SSMA treated mud exhibit excellent temperature stability
Thomas (1982)	Starch and CMC Polymer Mud	-Temperature	- Ineffective above 225° F and 200° F respectively

(Table 2.1 continued)

Son et al. (1984)	VSVA Mud	-Temp.,400° F	- Compared the results with PHPA mud and found that VSVA mud was more stable than PHPA mud
Clements et al. (1985)	Ligno-sulfonate Mud	-Temp., 450° F -Static aging, 16 hrs.	- Stable rheological properties and good tolerance of electrolyte concentration
Block (1985)	Alumina Gel Drilling Fluid	-Temp., 350° F	- Tartrate, citrate, sulfate stabilizes rheology and poly vinyl-alcohol stabilizes fluid loss properties
Hille (1985)	VSVA Copolymer Drilling Fluid	-Temp., 392° F	- Stable with high electrolyte concentration - Reduce Fluid loss, pipe sticking and thermo-gelling problem
Perricone et al. (1986)	AMPS/AM Drilling Fluid	Temp., 350° F	- Effective filtration control agent
Adelina et al. (1987)	VSVA treated Salt Water Mud	-Temp. 150° F-400° F -Press., 300 psi -Aging: static & dynamic	- PV, YS, GS and API Fluid loss is greater in dynamic aging

(Table 2.1 continued)

Al-Marhoun & Rahman(1987)	Water-base Mud (bentonite)	-Temp., 347° F -Dynamic Aging, 24 hrs.	- Viscosity, YS in HTHP viscometer decreases with temp.
Fisk and Jamison(1988)	Oil-base and Water-base Mud	-Temp., 184° F -Press., 20,305 psi	- Oil-base mud is characterized by logarithmic and water-base mud is chracterized by linear viscosity as a function of temperature - Pressure has negligible effect on dynamic filtration rates
Alderman et al. (1988)	Water-base Mud (bentonite)	-Temp., 266° F -Press., 14500 psi	- High shear viscosity decreases with temp. - Density increases with pressure - Yield point is independent of pressure and weakly dependent on temperature
Al-Marhoun & Rahman(1988)	Polymer Drilling Fluid	-Mud Composition -Temp., 446° F	- Synthetic copolymers are most effective additives for severe condition - Partial substitution of bentonite by attapulgite improves drilling fluid performance
Elson et al. (1988)	Lime base Drilling Fluid	-Temp., 300° F -static aging, 16 hrs.	- Use of VSVA, low molecular wt. polyacrylamide and sulfonated asphalt provide stable rheological properties

time so far considered by these investigators are 460°F [12] and 2 days [6] respectively. As their studies show that both temperature and aging have effects on drilling fluid properties. This study has investigated the combined effect of temperature as high as 490°F and aging time upto 30 days on water-base drilling fluids. The reason for taking maximum temperature of 490°F is that it is very close to the equipment limitation of maximum 500°F. The reason for maximum aging time of 30 days is that the effect of aging was found to be very small with the high aging time.

CHAPTER 3

CHAPTER 3

EXPERIMENTAL SET-UP

In this chapter, detailed description of the apparatus , materials and experimental procedures used in this study are presented.

3.1 APPARATUS

The experimental apparatus used in this study consisted of a Fann Model 70 Viscometer and a Baroid Roller Oven. The details of each apparatus are given below.

3.1.1 Fann Model 70 Viscometer

The Model 70 Viscometer (Figure 3.1) is a direct-indicating coaxial cylinder viscometer to measure fluid rheological properties under high pressure (20,000 psig) and temperatures ($500°F$). It consists of three major components : the Control Console, the Remote Test Station and the Test Cell. The specifications of Fann Model 70 HTHP Viscometer is shown in table 3.1.

3.1.1.a The Control Console

This component contains all controls and displays, power supplies, the pressurization pump and reservoir, the over-pressure relief rupture disk, and

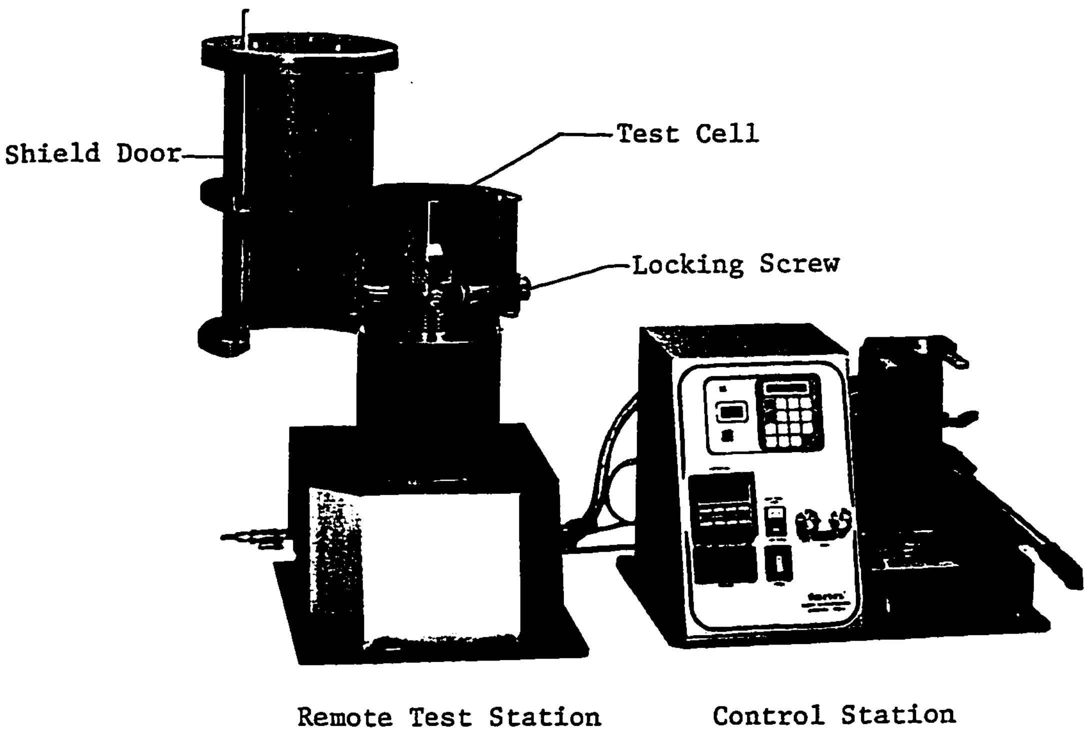


Fig.3.1: Fann Model 70 HTHP Viscometer [Ref.27].

Table 3.1: Fann Model 70 HTHP Viscometer Specifications:

Rotor Speed, rpm (nominal)	3-600
Fixed Speeds (rpm)	600, 300, 200, 100, 3
Rotor Radius, cm	1.8415
Bob Height, cm	3.805
Shear Gap in Annulus, cm	0.1170
Shear Rate Constant, $\sec^{-1}/rpm$	1.7023
Maximum Use Temperature, $°F$	500
Minimum Use Temperature	Ambient
Pressure Rating, psig	20,000
Sample Volume, ml (nominal)	175
Power	115/230 V, 60/50Hz, 1KVA
Viscosity Range, cp	0-300, @ 300 rpm
Minimum Viscosity, cp	5, @ 600 rpm
Maximum Viscosity, cp	300, @ 300 rpm

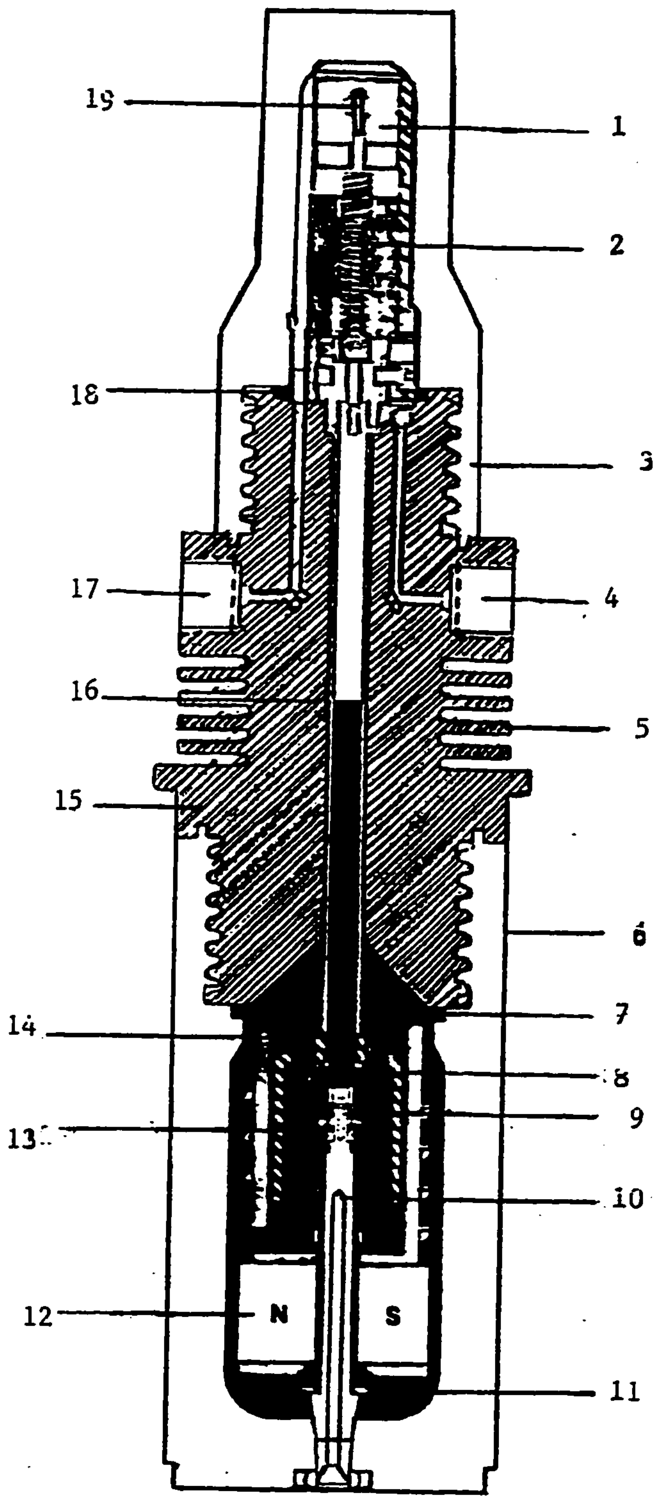
a removable cell preparation station.

3.1.1.b The Remote Test Station

The Remote Test Station contains the magnetic torsion angle sensor, the magnetic cell drive, the cell heaters, the water cool-down system, temperature sensor, and cooling fans. The Remote Test Station also contains a vertical, cylindrical safety shield which is designed as a secondary back-up in case of a cell failure at high pressures. High pressure tubing connections to the cell are made without the use of tools. The shield is hinged so that the top portion can be swung out for loading the Test Cell. Fluid property measurements cannot be made unless the top of the shield is closed.

3.1.1.c The Test Cell

The cell is made of a corrosion-resistant alloy and is designed for 20,000 psig operation at $500°F$. It includes a torsion assembly that uses an American Petroleum Institute (API) type bob and rotor geometry. The rotor has external flights to induce circulation. It is driven by a magnet. The movement of the torsion assembly is transmitted outside of the cell by another magnet which turns with the torsion assembly. Figure 3.2 shows a test cell and its accessories.



1. Torque Sensor Magnet
2. Spring Assembly
3. Cap
4. Pressure Inlet Port
5. Cooling Fins
6. Cell
7. Lower High Pressure Seal
8. Bob
9. Lower Pivot
10. Thermowell
11. Rotor Bushing
12. Rotor Drive Magnet
13. Main Rotor Bearing
14. Rotor
15. Coupling
16. Oil/Sample Interface
17. Bleed Port
18. Upper High Pressure Seal
19. Upper Pivot

Fig.3.2: Test Cell and Accessories [Ref.27].

3.1.2 Baroid Roller Oven

Baroid Roller Oven is shown in Figure 3.3. It is insulated, thermostatically controlled Oven with stainless steel exterior and interior for heating and for agitating sample in suitable container (Aging Cell) as shown in Figure 3.4. Roller Ovens are primarilly designed for laboratory use to simulate the heating and agitation that the drilling mud is subjected to while being circulated down the hole and back to the mud pit. Agitation is particularly important when investigating muds in which the base exchange reactions occur and in the determination of thermal stabilities of both mud and mud additives.

Aging cells with 5 rollers are used for aging purposes. The rollers along with the aging cells rotate at an approximate speed of 50 rpm.

3.2 MATERIALS

The mud is formulated according to the formulation obtained by Al-Marhoun and Rahman [24]. This mud was found to be optimum formulation for water-base drilling fluid system at the conditions of elevated bottom hole temperature and at high influx of electrolytes.

The materials used for the mud sample of this study were as follows:

(a) Fresh water: distilled water was used as the continuous phase for all the

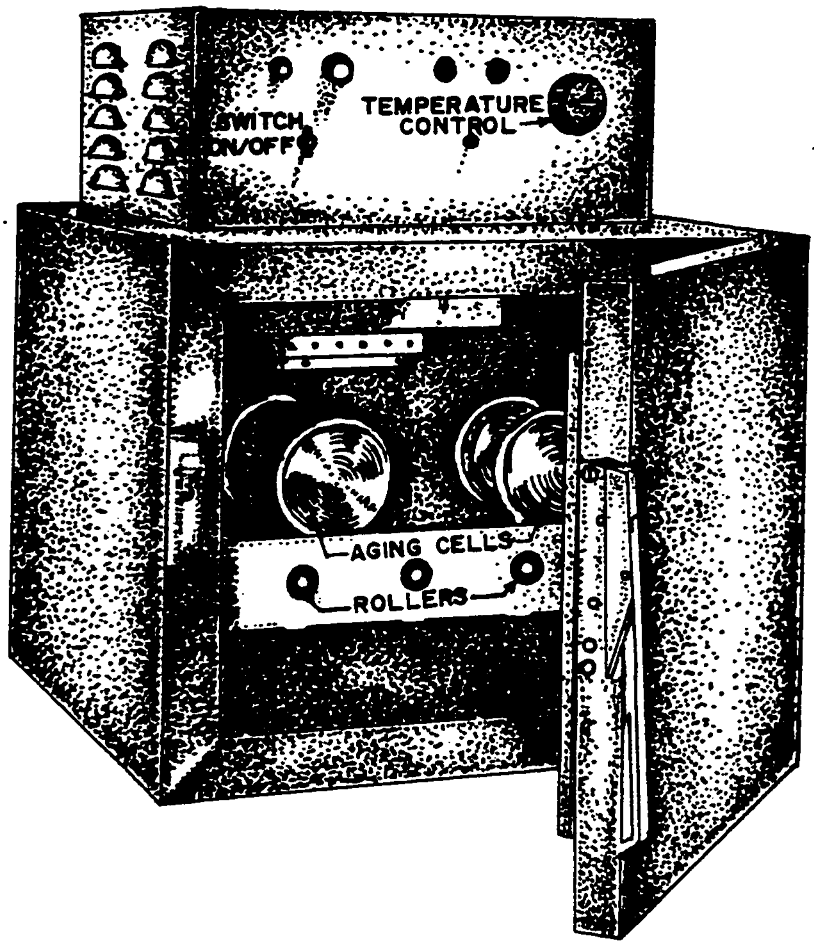


Fig.3.3: Baroid Roller Oven [Ref.26].

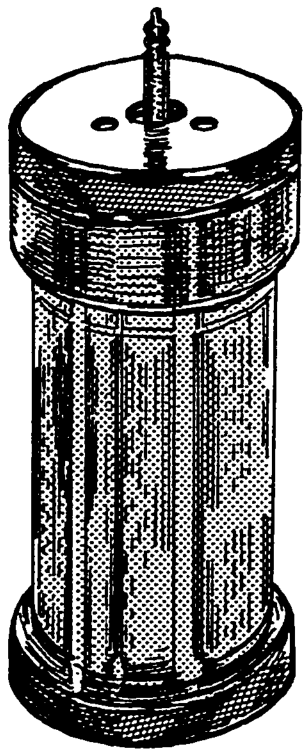


Fig.3.4: Baroid Aging Cell [Ref.26].

experiments where the different components are blended with it to form the drilling fluid.

(b) Wyoming bentonite: It was used as the clay mineral to develop viscosity. Two grams of bentonite were used in 100 grams of fresh water.

(c) Attapulgite: Three grams of attapulgite were used in 100 grams of fresh water as a highly temperature and electrolyte resistant clay minerals.

(d) VSVA (vinylsulfonate/vinylamide): One and a half grams of VSVA were used in 100 grams of fresh water to make the drilling fluid more compatible at high temperatures.

(e) Sodium Chloride: Three grams of sodium chloride were added to the bentonite suspension to attain maximum gel strength of the drilling fluid.

(f) Calcium hydroxide(Lime) and Gypsum: Often it has been experienced that the clay mud fails to retain its properties when drilling cement, lime stone anhydrite and "gyp" formations. To make it compatible against these formations, the base mud was treated with gypsum and calcium hydroxide. 0.85 gram of gypsum and 0.28 gram of calcium hydroxide were added in 100 grams of fresh water.

Barite and SSMA were eliminated from the above formulation. Barite is inert and it does not react with other composition in the mud. Barite is used as weigthing material and it has no effect on rheological properties. Two copolymers(VSVA and SSMA) were used in the original formulation for the high temperature stability of the drilling fluid out of which only VSVA was used for this study.

The density of the drilling fluid was 1.0695 g/cm^3 and pH was measured as 9.8.

3.3 EXPERIMENTAL PROCEDURES

The experimental procedures followed for different instruments are as follows:

3.3.1 Procedure for Fann Model 70 Viscometer

(a) Test Cell Set-up

- With all parts clean and free from contaminants, the Baffle and Bob Shaft Assembly are screwed gently and very carefully onto the cell.
- The Rotor Assembly is carefully lowered into the cell and the cell (without sample) is carefully screwed onto the main coupling.
- Free rotation of the Torsion Assembly is checked before the cell cap is hand- tightened onto the cell body.
- The test cell is carefully lowered into the hot well of the Remote Test Station and the two port connectors as well as the locking screw are hand-

closed.

(b) Setting the Zero Offset

- The Zero Offset i.e., the numerical difference between the mechanical zero of the Torsion Assembly and the electronic zero of the magnetic sensor has to be not more than plus or minus 5 is set using the MENU option of the Control Console.

(c) Sample Placement

- Using a graduated cylinder and a funnel, 140 ml of the sample is carefully poured into the cell which is then lifted up and carefully screwed onto the coupling.
- 25 ml of the remaining sample is then injected in using a syringe through the sample port to bring the sample level just below the sample port.
- The cell top is then closed using its cap and the entire test cell is lifted off the stand and placed inside the hot well of the Remote Test Station . The two port connectors and the locking screw are installed and hand-tightened and the Shield Door of the Remote Test Station is slowly and carefully closed.

(d) Setting Temperature and Pressure on the Control Console

- The power switch on the Control Console as well as the cooling water are both turned on at their sources.

- The temperature controller is turned on but the heating option is deactivated.
- The vent valve is opened 3 times and the pump stroked about 20 times to expel any existing air bubbles before the vent valve is reclosed to pressurize the system.
- The test cell is pressurized to about 3000 psig and watched for about 5-10 minutes to determine if the system is leaking. Any leak must be rectified before proceeding to the next step. All runs are conducted at constant pressure of 3000 psig.
- A final temperature is selected with the temperature controller's display, 'Up Arrow/Yes', 'down Arrow/No' keys as well as the multi-set point pre-programmed mode facilities. All data are collected at 77, 122, 212, 302, 392 and 490°F.
- Using the speed select switch, the system shear rate is activated to 200 rpm to ensure that the dial readout behaves as expected.
- The START/STOP key on the temperature controller is pressed to begin the heating process. When the desired temperature for the test is achieved, the desired pressure for the test is adjusted with the pump and vent valve.

Conducting the Test

- Start taking data i.e., the shear rate and the dial reading, when the required temperature and pressure is achieved.

- Pressure and temperature can be reset for another fresh data collection as required.
- At the end of the test, the temperature set point is changed to about $70°F$ and the cell is left pressurized. The water cooling is turned on and run until the temperature has dropped to about $85°F$.
- When the cell has cooled (after the temperature controller is disabled), the cell pressure is released using the vent valve.
- The test cell is now removed and the sample removed as well. All parts are now disassembled and properly cleaned.

3.3.2 Baroid Roller Oven

Principally, the operation of the roller oven consists of placing the cell with its sample in the oven, plugging it into its proper current source, setting the thermostat dial to the appropriate temperature and then setting the roller jars rolling by turning on the switch. Detailed test procedures are described below.

Test Procedure

- After the mud sample has been prepared according to the desired specification, it is poured into a clean 500 ml aging cell.
- The inner cap is put in place at the top of the cell and the outer cap is

placed on top of the inner cap and tightened in place by means of the center screw nut.

- The cell and its content is placed into the aging oven, the desired aging temperature is adjusted at $77°F$ which was above the room temperature. The reason for selecting the aging temperature at $77°F$ was to avoid any fluctuation in room temperature. In this study, the mud samples are aged at 0 day, 1 day, 3 days, 7 days, 10 days, 15 days, 20 days and 30 days in the roller oven.
- After the desired aging time has elapsed, the cell is removed from the oven and the top and inner caps are removed. The sample is now ready to be tested.

CHAPTER 4

CHAPTER 4

RESULTS AND DISCUSSIONS

Before presenting the results, the various parameters which describe the flow behavior of drilling fluids are defined; these are: effective viscosity (μ_e), plastic viscosity (μ_p), yield point (YP) and gel strength (GS).

Effective Viscosity: It is measured as,

$$\mu_e = 1/2\ \theta_{600},$$

where θ_{600} is the dial reading at 600 rpm. Therefore, effective viscosity is measured by the dial reading at shear rate of 1022 sec^{-1} divided by 2 and is expressed in mPa.s.

Plastic Viscosity: The plastic viscosity is measured as,

$$\mu_p = (\theta_{600} - \theta_{300}),$$

where θ_{300} is the dial reading at 300 rpm and is expressed in mPa.s.

Yield Point: The yield point is measured as,

$$YP = 5.1\ (\theta_{300} - \mu_p) \text{ in dPa.}$$

Gel Strength: This is a measure of minimum shear stress that is required to create the flow of the drilling fluid. Two readings are generally taken: the first reading is taken immediately after the agitation of the mud in the cup, and the second reading is recorded after the mud is kept for 10 minutes of rest. These readings are referred to as the initial gel strength and 10 minutes gel strength respectively. The initial gel strength shows the structural viscosity of the mud under circulation and the 10 minutes gel strength shows the resistance to flow after a period of rest. The gel strength is measured as,

$$GS = 5.1\ \theta_3 \text{ in dPa},$$

where θ_3 is the dial reading at 3 rpm.

Exponent of Power-Law (n): It is determined by using the following equation:

$$n = 3.32 \log (\theta_{600} / \theta_{300}),$$

where θ_{600} and θ_{300} are the dial reading at 600 and 300 rpm respectively. The value of n indicates the degree of deviation from Newtonian behavior of the fluid. If n is unity, then the fluid is Newtonian; if n is less than unity, then the fluid is pseudoplastic(shear-thinning). The lower the n value, the more shear-thinning the fluid and this type of rheology is highly desirable for the drilling fluids as the drilling fluid will be thin at the drill bit(high shear rates) and sweep cuttings away, and thick in the annulus(lower shear rates) and keep cutting suspended [17]. Increase in drilling rates with a shear-thinning mud systems has been described by Walker [30, 31].

The Consistency index (k): It is determined by using the following equation:

$$k = \frac{\theta_{600}}{(1022)^n},$$

and is usually expressed in dynes/cm^2. k is a viscosity -like term, and is equal to the viscosity when shear rate is unity.

4.1 EXPERIMENTAL RESULTS

Details of the experimental results are tabulated in the Appendix. Values of effective viscosity, plastic viscosity, yield point, gel strengths (10 sec. and 10 min.) as a function of temperature are presented respectively in Figures 4.1 through 4.5 with the aging time as a parameter. Each curve of these Figures represents the results for a different aging time. Values of shear stress as a function of shear rate for different temperatures(at fixed aging time) are presented in Figures 4.6 through 4.13 and values of shear stress as function of shear rate for different aging time(at fixed temperature) are presented in Figures 4.14 through 4.19.

4.2 DISCUSSIONS

4.2.1 EFFECTS OF TEMPERATURE

The effect of high temperatures on drilling fluid can be attributed to the complicated interplay of several causes, among which the following are prominent: reduction of the degree of hydration of the counterions, changes in the electrical double-layer thickness, increased thermal energy of the clay micelles, reduction of the viscosity of the suspending medium and increased dispersion of associated clay micelles. All these processes take place simultaneously, and an interpretation of the observed results is possible only in those cases where some of the effects are predominent, so that they can be identified [4].

As shown in Figures 4.1 through 4.5, effective viscosity, plastic viscosity, yield point and gel strengths decrease gradually with the increase in temperature for all values of aging time. These changes in rheological properties can be explained according to the investigation done by Al-Marhoun and Rahman [24]. According to them, these changes in rheological properties are due to the effect of gypsum and lime added to the mud system. With the application of heat,both gypsum and lime release a large amount of calcium ions in aqueous solution. Due to the high charge density of Ca^{++}, the anionic copolymer VSVA (vinylsulfonate/vinylamide) change its configuration from an extended to a tightly coiled structure. Under such circumstances, copolymers loose their ability to protect the clay platelets. Ca^{++} ions replace the Na^{+} ions from the crystal lattice of the clay platelets, thus resulting in calcium-base clay. Due to the interparticle forces of calcium-base clay, the platelet aggregates. As the ion exchange continues, the platelets collapse upon each other and leads to a state of aggregation. As a result of

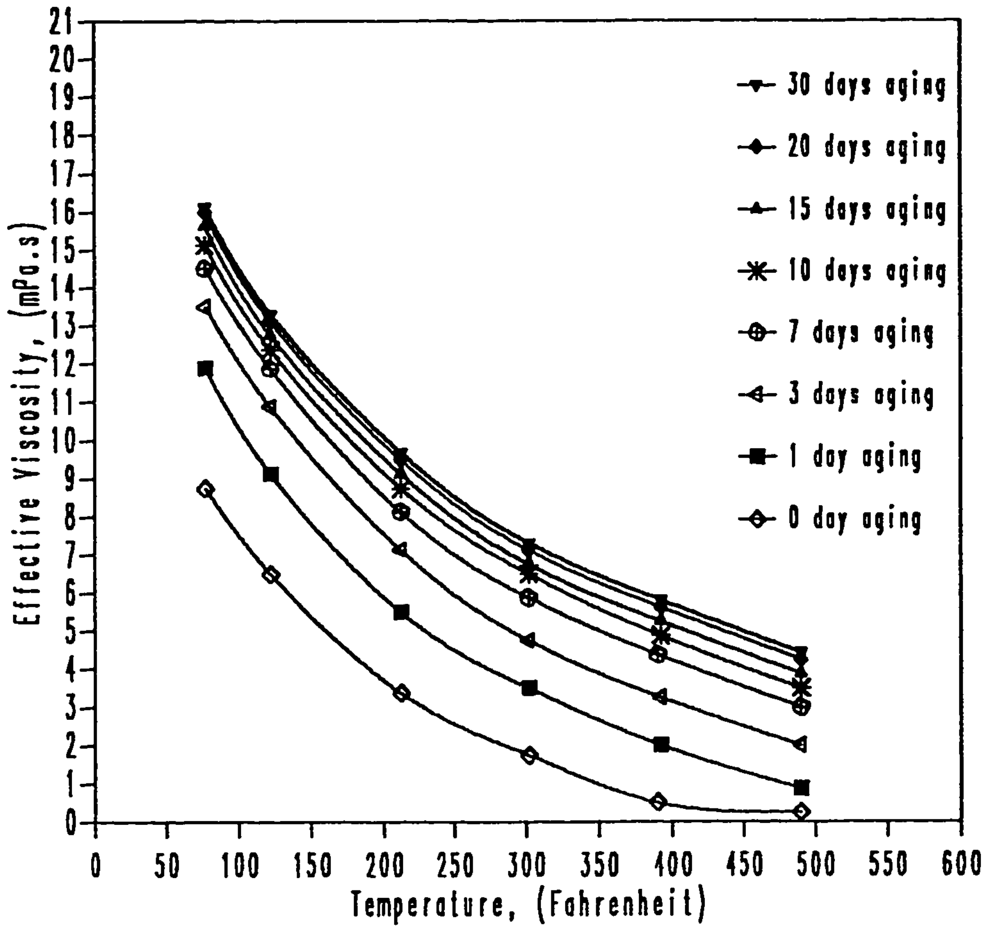


Fig.4.1: Effective Viscosity as a Function of Temperature for Different Aging Time at 3000 psig Pressure.

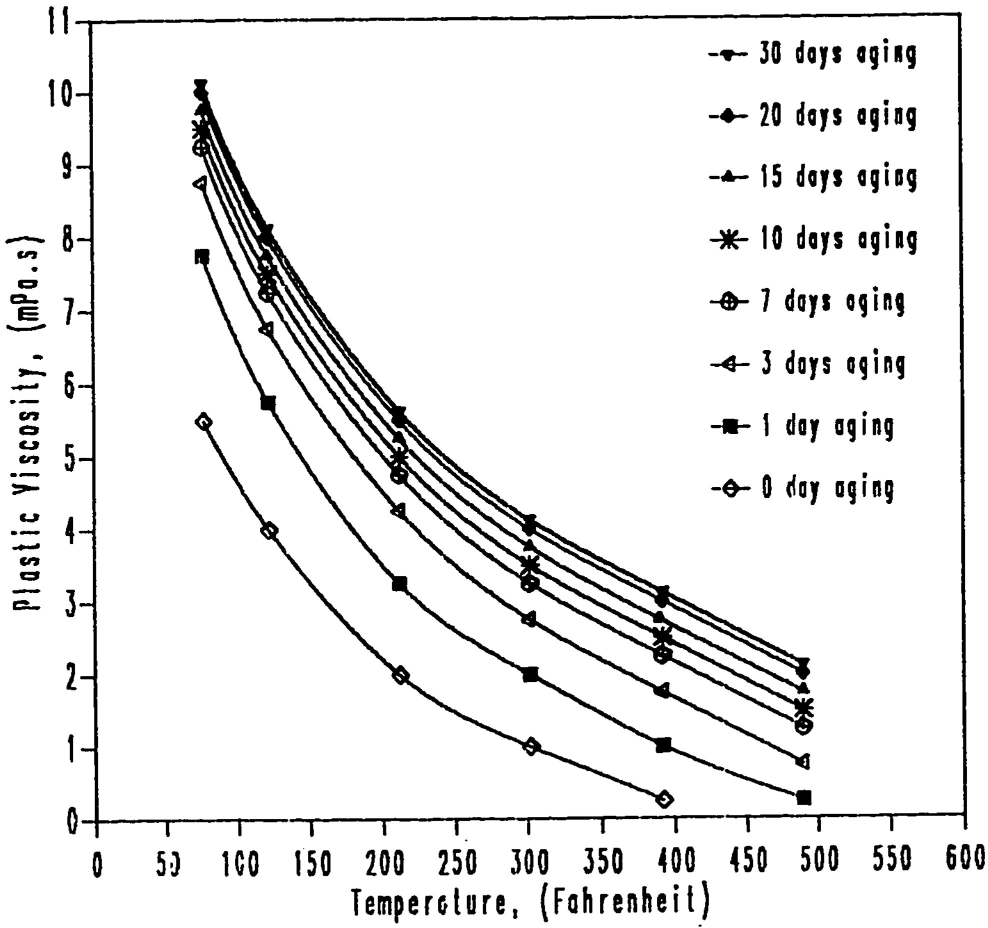


Fig.4.2: Plastic Viscosity as a Function of Temperature for Different Aging Time at 3000 psig Pressure.

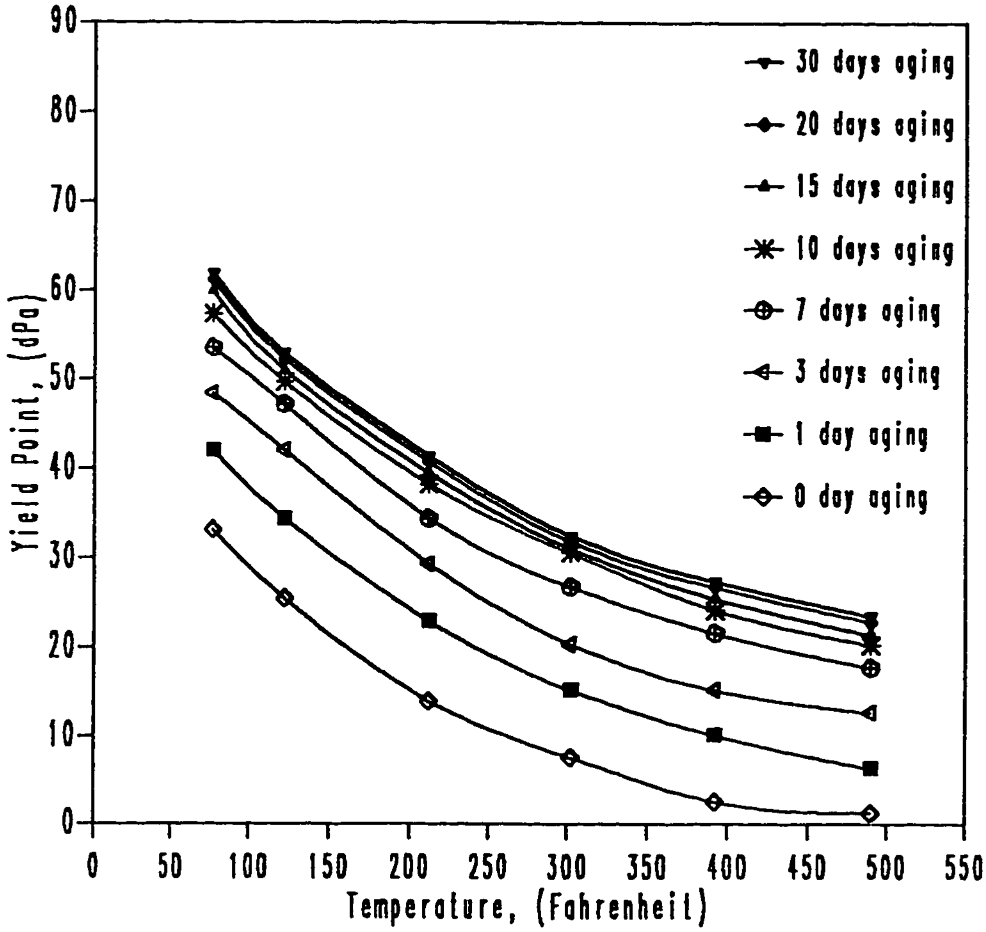


Fig.4.3: Yield Point as a Function of Temperature for Different Aging Time at 3000 psig Pressure.

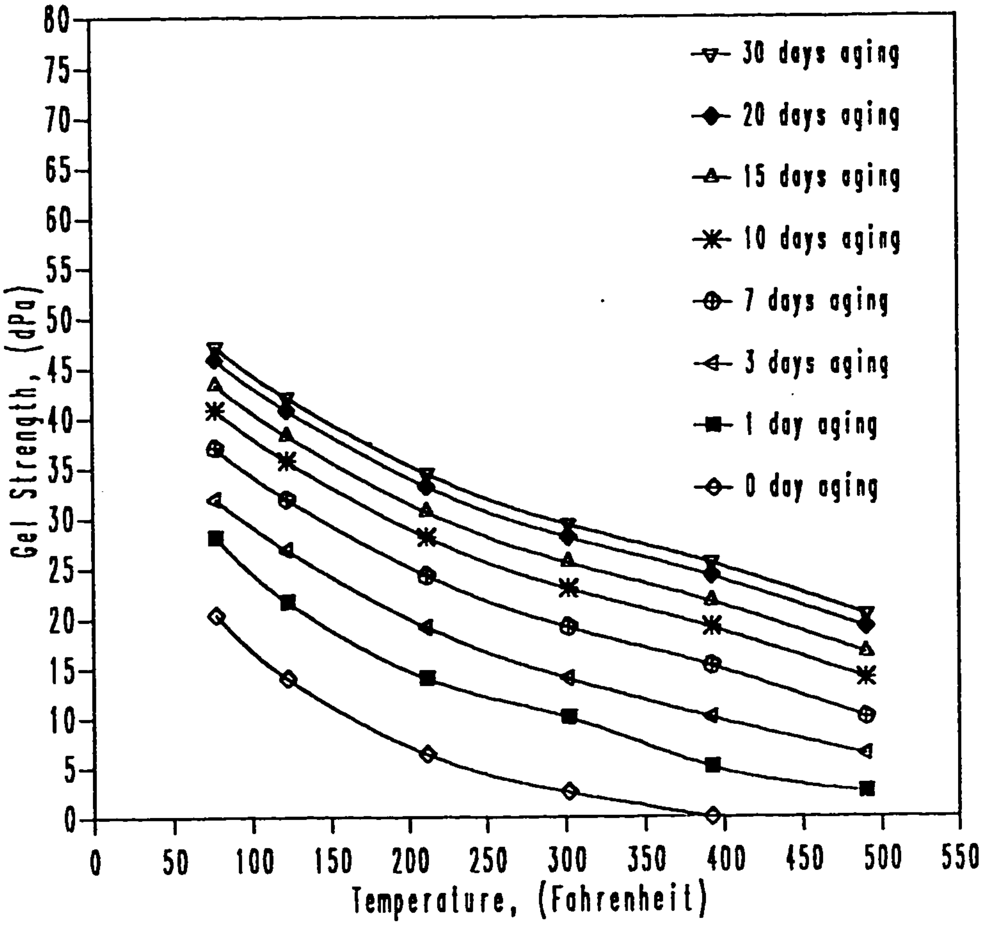


Fig.4.4: Initial Gel Strength (10 sec) as a Function of Temperature for Different Aging Time at 3000 psig Pressure.

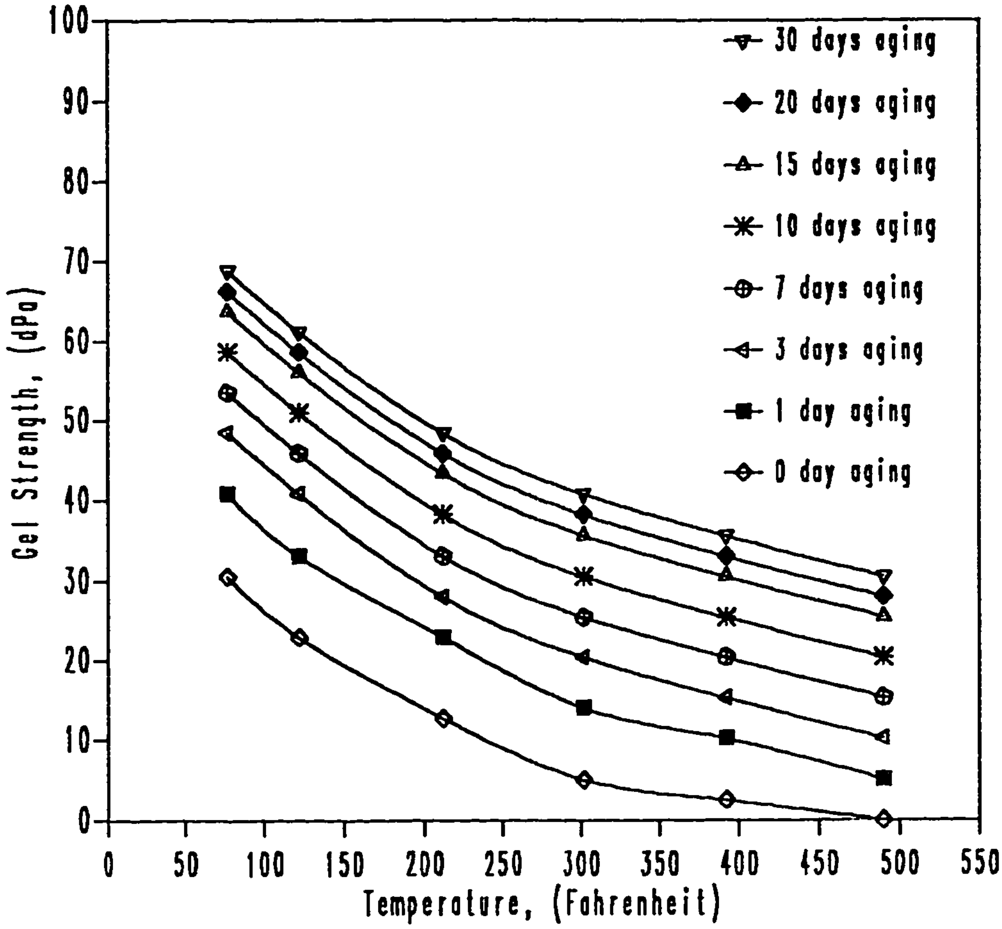


Fig.4.5: 10 Minutes Gel Strength as a Function of Temperature for Different Aging Time at 3000 psig Pressure.

continuous flocculation and aggregation of the platelets, there is an overall reduction in solid volume, thus enabling the clay aggregates to move freely through the aqueous phase with consequent lowering of the internal friction. As the internal friction of the suspension decreases, the viscosity diminishes too(Figures 4.1 and 4.2). The state of aggregation is the association of individual platelets face to face to form loose stack. This aggregation causes a reduction in (a) the number of units available to build gel structure, and (b) the surface area available for particle interaction and thus the yield point and gel strength are also decreased with temperature(Figures 4.3 through 4.5). The results of this study are in good agreement with the results obtained by Al-Marhoun and Rahman except that they reached a maximum temperature of $446°F$ and this study reached a maximum temperature of $490°F$ (equipment limit) and found that the drilling fluid is quite stable for high temperature.

Figures 4.6 through 4.13 show that: (1) for a particular temperature, shear stress increases with shear rate, (2) for the same shear rate, shear stress decreases with increasing temperature and temperature effects are diminishing with increase in temperature. This is due to the fact that copolymers and bentonite clay suffer severe degradation due to the application of heat as well as mechanical shearing. As the polymer degrades, the clay platelets starts dehydrating, the platelets approach each other so

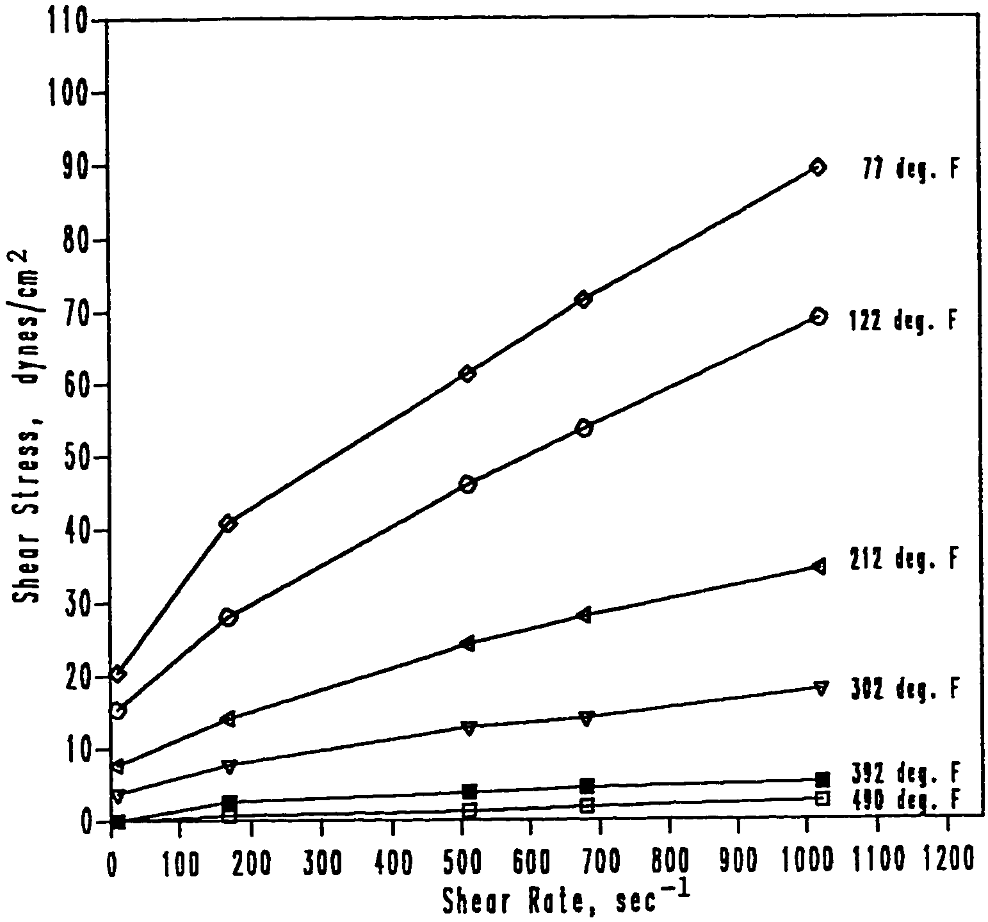


Fig.4.6: Shear Stress as a Function of Shear Rate for Different Temperature at 0 Day Aging Time and 3000 psig Pressure.

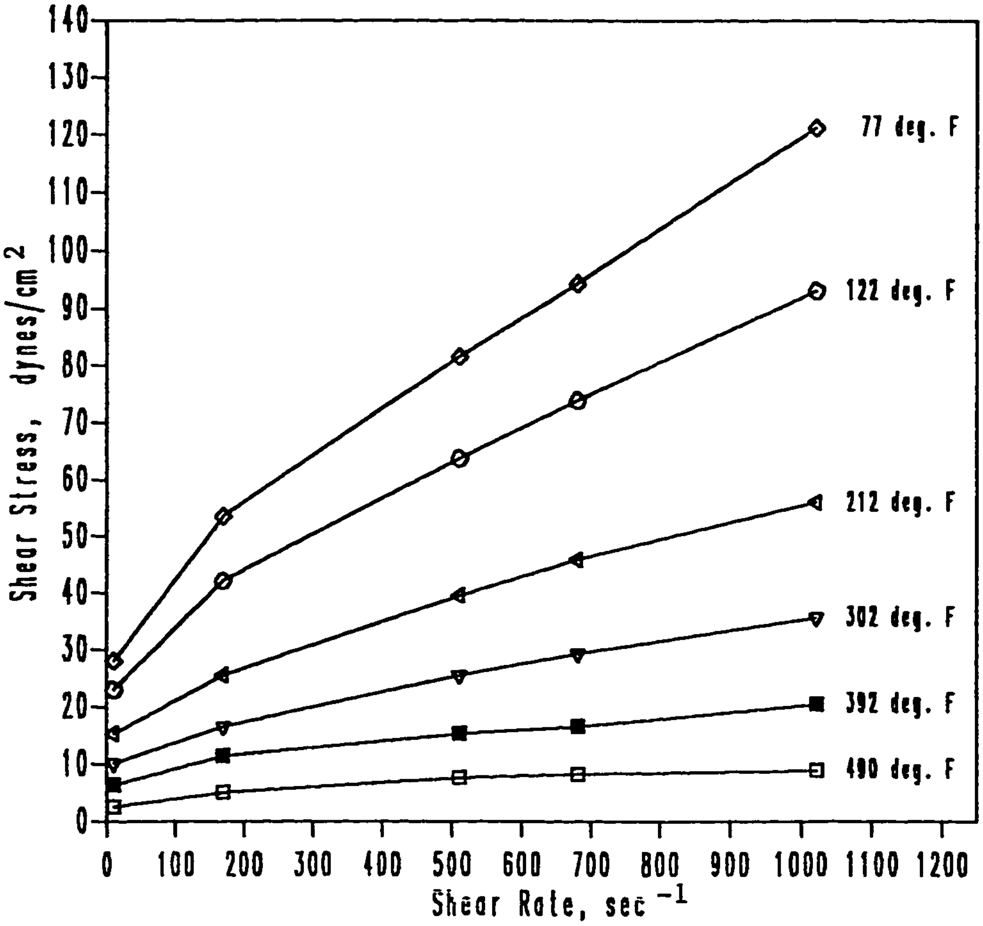


Fig.4.7: Shear Stress as a Function of Shear Rate for Different Temperature at 1 Day Aging Time and 3000 psig Pressure.

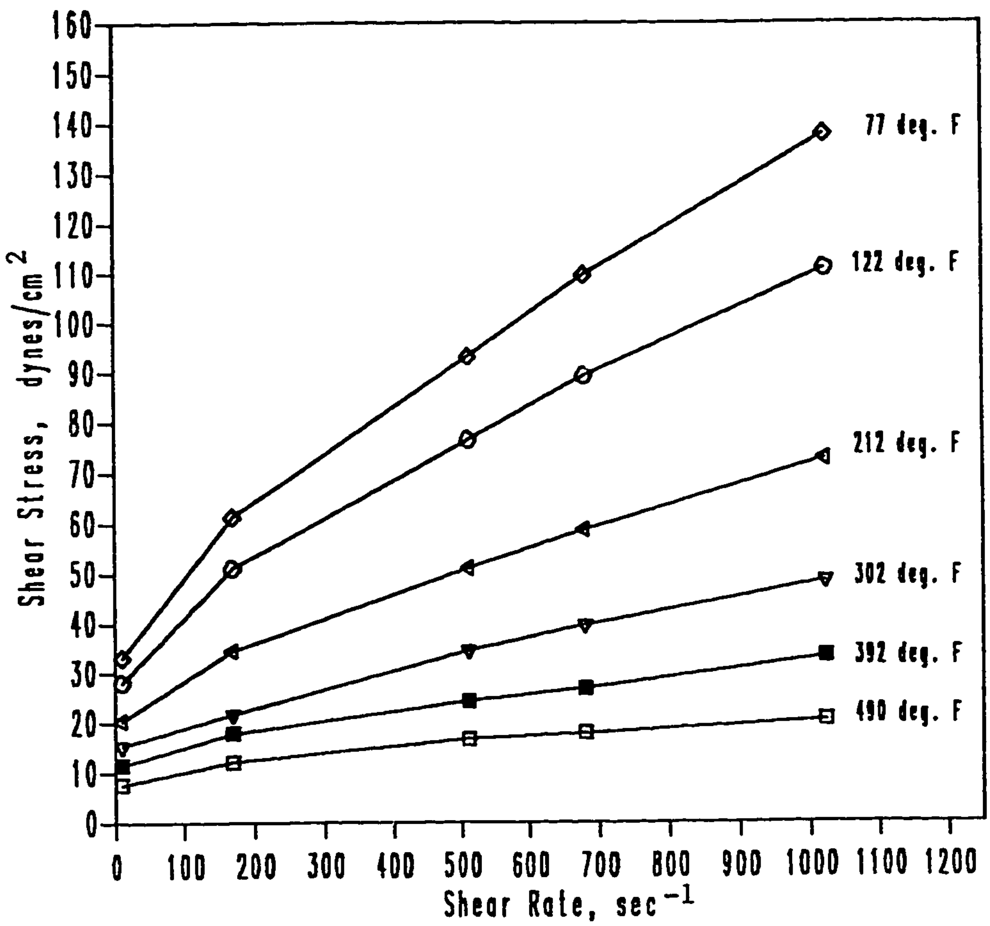


Fig.4.8: Shear Stress as a Function of Shear Rate for Different Temperature at 3 Days Aging Time and 3000 psig Pressure.

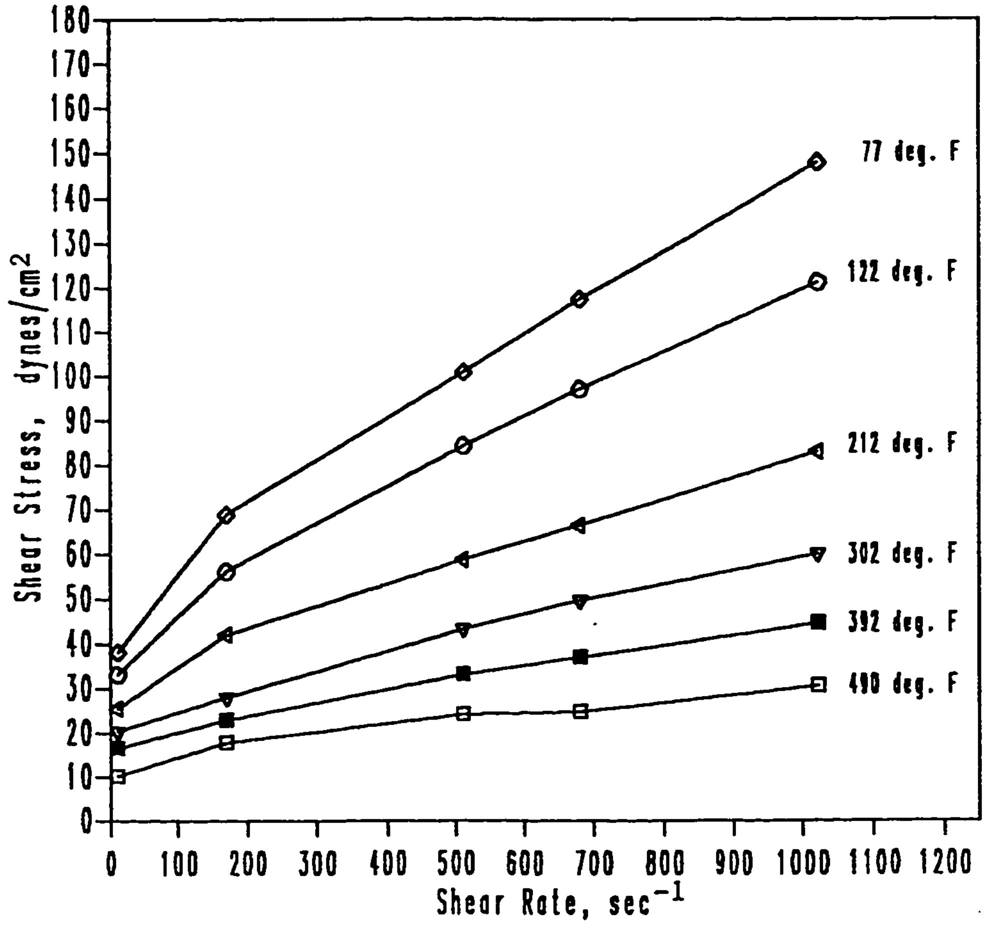


Fig.4.9: Shear Stress as a Function of Shear Rate for Different Temperature at 7 Days Aging Time and 3000 psig Pressure.

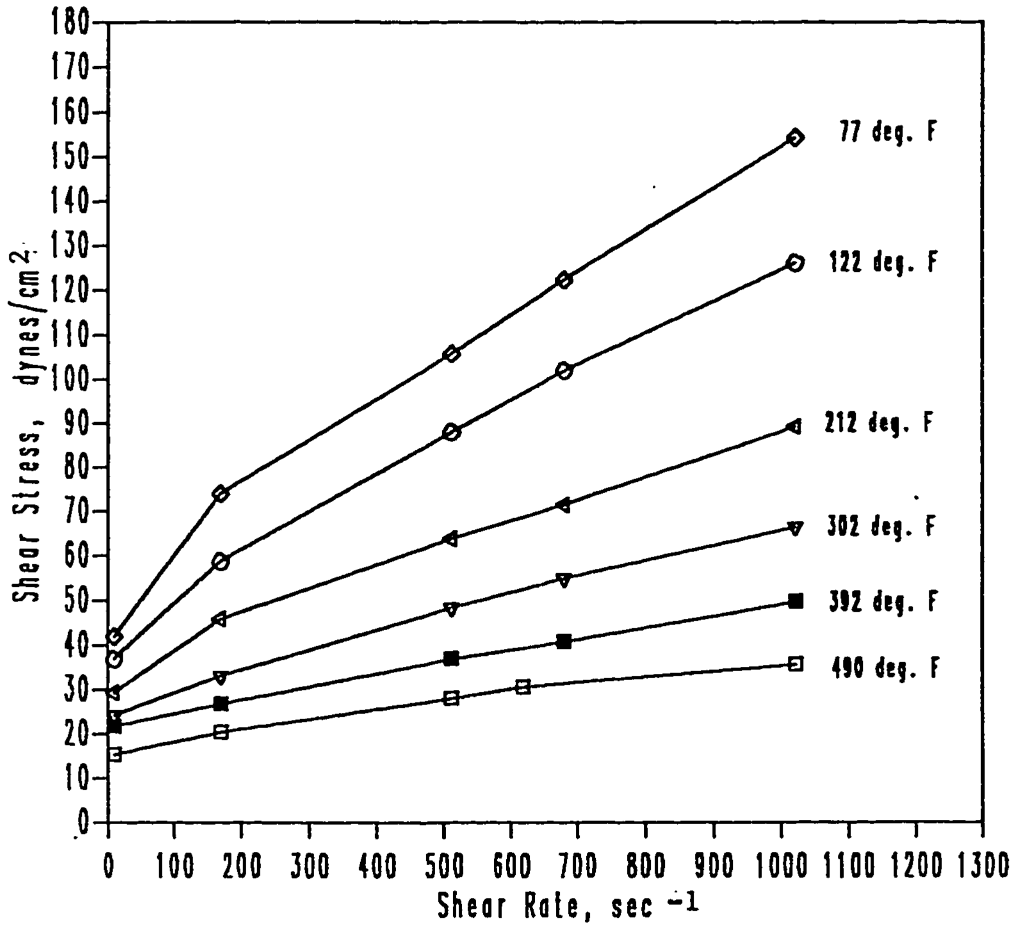


Fig.4.10: Shear Stress as a Function of Shear Rate for Different Temperature at 10 Days Aging Time and 3000 psig Pressure.

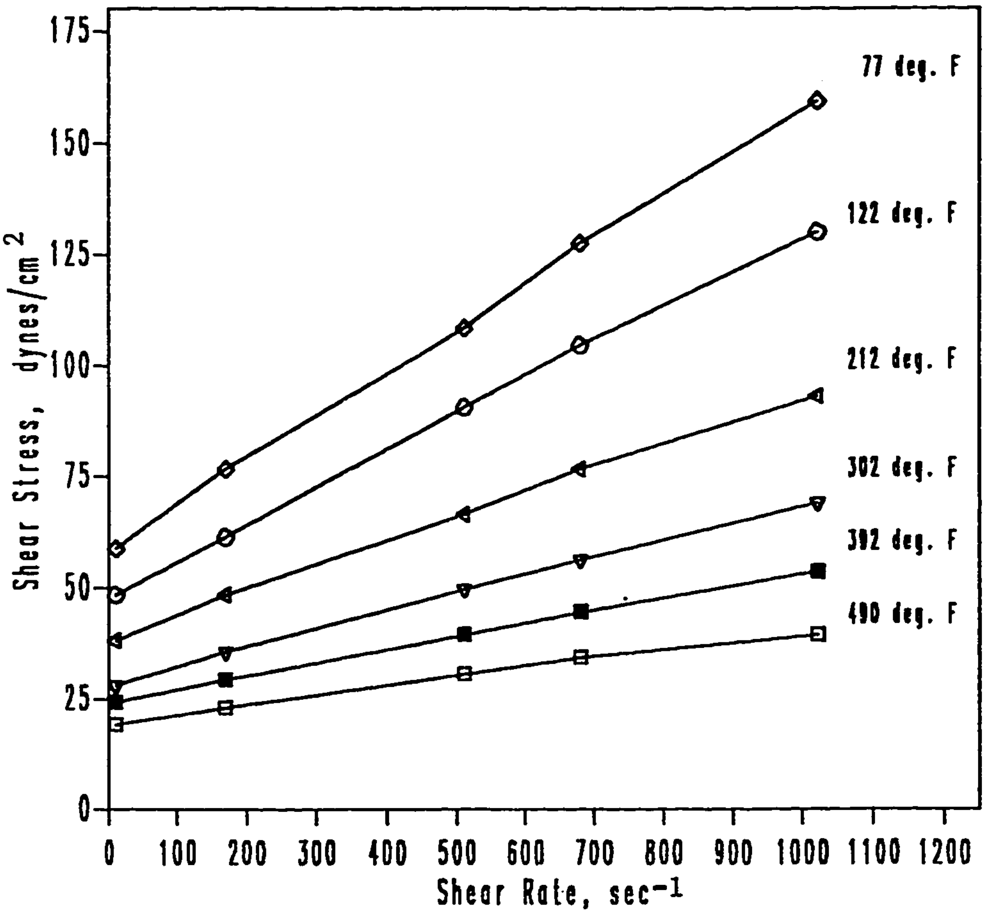


Fig.4.11: Shear Stress as a Function of Shear Rate for Different Temperature at 15 Days Aging Time and 3000 psig Pressure.

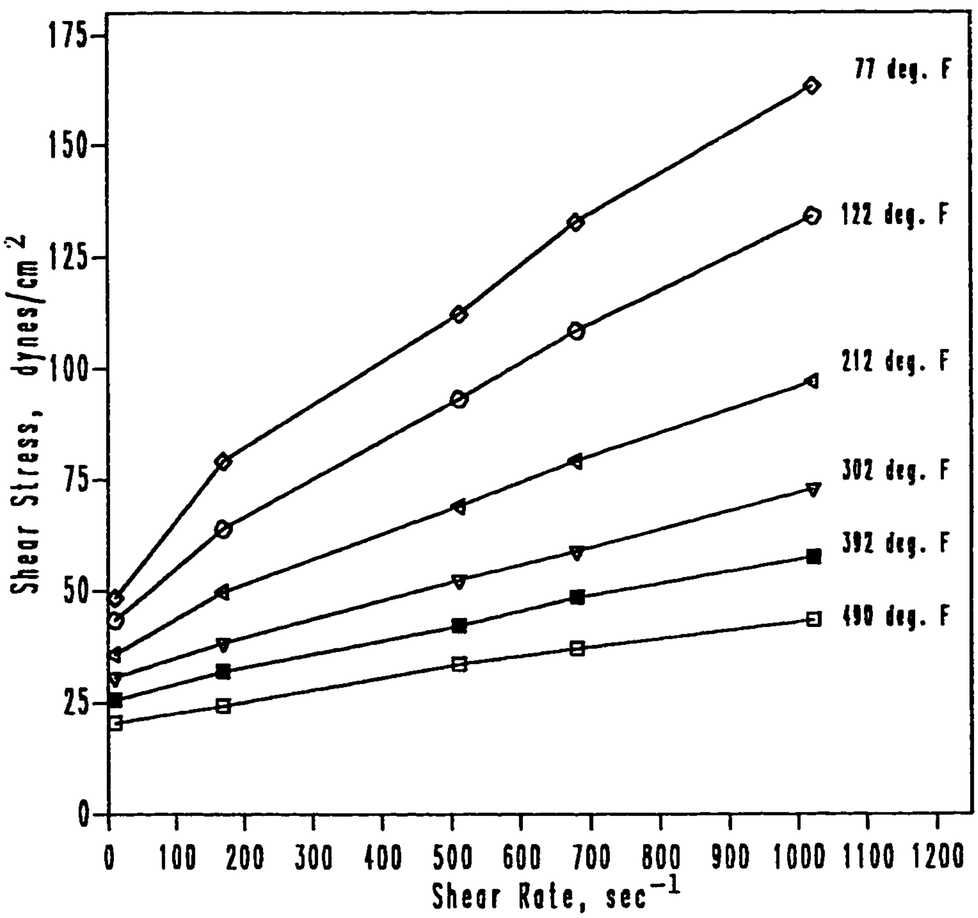


Fig.4.12: Shear Stress as a Function of Shear Rate for Different Temperature at 20 Days Aging Time and 3000 psig Pressure.

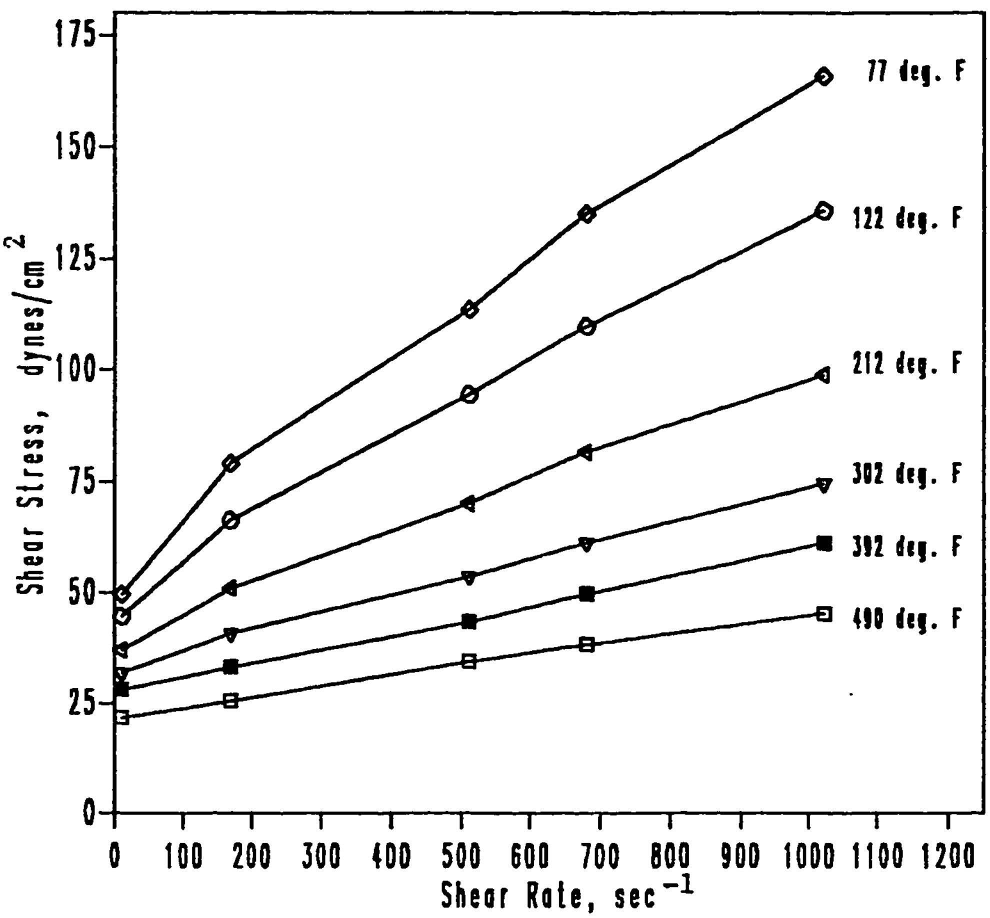


Fig.4.13: Shear Stress as a Function of Shear Rate for Different Temperature at 30 Days Aging Time and 3000 psig Pressure.

closely that the attractive forces dominate, resulting in a state of dispersion with edge to face contact of the platelets. Increase in temperature causes the platelets to aggregate, and ultimately leads to a state of aggregation and flocculation resulting in low rheological properties. Presence of attapulgite compensate this effect to some extent. The polymer posses a high density of multiple charge and remain adsorbed on the clay platelets in the presence of Ca^{++} ions. Due to the carbon - carbon backbone , the VSVA copolymer is more stable to heat and is able to protect the bentonite platelets from dehydration to certain extent at high temperature and as such there is no sharp change in rheological properties of the drilling fluid. Another reason is that in HTHP viscometer, the mud sample is subjected to continuous shear rate. The high shear rate prevents the bentonite platelets from building structure like house of cards and thus there is gradual change in rheological properties. The results of the effect of temperature on shear stress-shear rate relationship follows the same trend as found by Hiller [4]. He used 4 percent pure sodium montmorillonite to which 5 meq./litre of NaOH was added and measured the shear stress-shear rate values for 78 and 350°F at constant pressure of 8000 psi (Figure 2.2). It is observed that shear stress for a particular temperature increases with shear rate, but shear stress at a given shear rate decreases with the increase in temperature. As data was collected only at two temperatures, no specific conclusion was drawn about temperature effect. In this study, data is collected at 77, 122, 212, 302, 392 and $490°F$ and the results show that temperature effect is decreasing and after $392°F$, temperature effect on shear stress-shear rate is very small.

4.2.2 EFFECTS OF AGING

The effect of aging time on the rheological properties of drilling fluid has been studied. The results are shown in Figures 4.1 through 4.5 and also in Figures 4.14 through 4.19. Figures 4.1 through 4.2 show that the viscosity for a particular temperature increases with the increase in aging time and aging effects are diminishing with the increase in time. This may be due to the fact that the degree of dispersion and flocculation increase when muds are aged dynamically. Rheological properties of mud increased at both high and low shear rates after the mud is rolled dynamically. This increase in properties must be ascribed to an increase in the degree of dispersion. Dispersion means the subdivision of large particles into small, and more specifically, the separation of clay particles into a large number of particles containing fewer platelets per particle by hydration and agitation. As investigated by Al-Marhoun and Rahman [24], use of attapulgite increases the rate of dispersion. This is because of the hydration mechanism of attapulgite. The surface energy of attapulgite clay is very low. The viscosity of the suspension is developed due to the brush heap structure formed by the clay particles. The application of shearing activates the surface charges causing more hydration of clays. The higher the hydration, the more

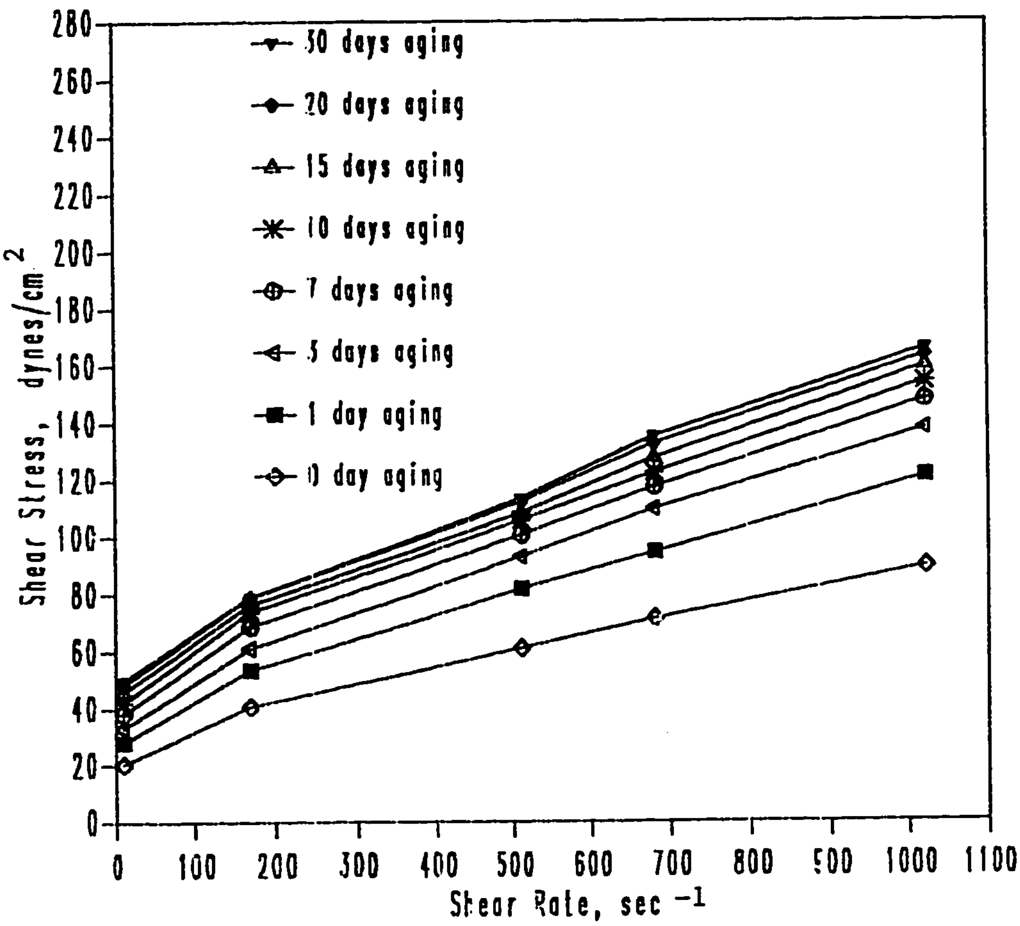


Fig.4.14: Shear Stress as a Function of Shear Rate for Different Aging Time at 77°F Temperature and 3000 psig Pressure.

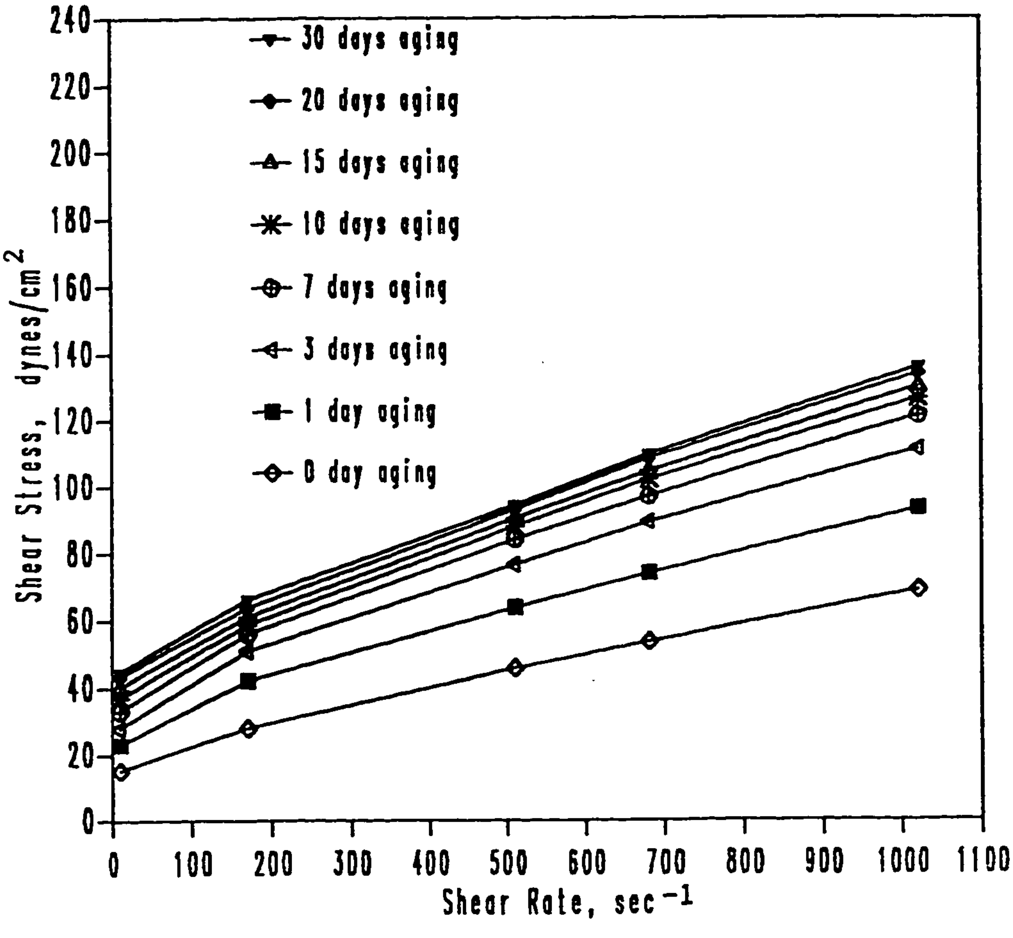


Fig.4.15: Shear Stress as a Function of Shear Rate for Different Aging Time at 122°F Temperature and 3000 psig Pressure.

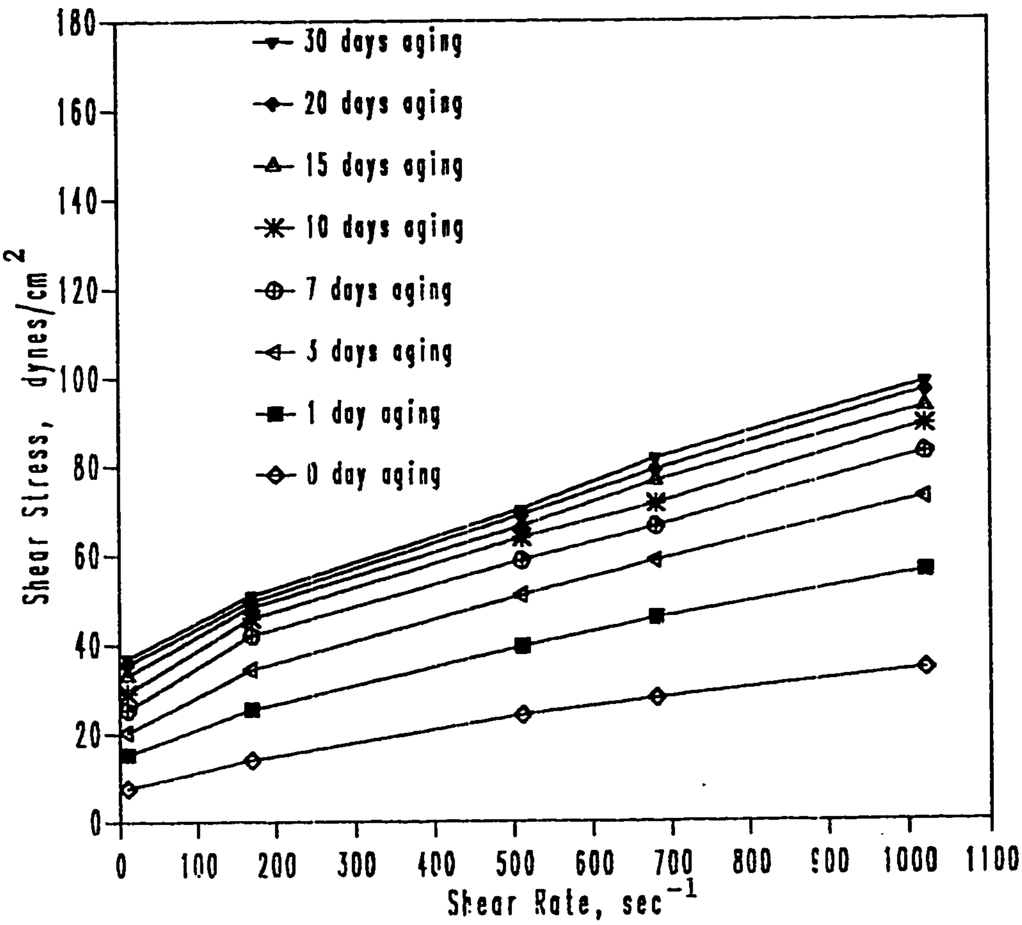


Fig.4.16: Shear Stress as a Function of Shear Rate for Different Aging Time at 212°F Temperature and 3000 psig Pressure.

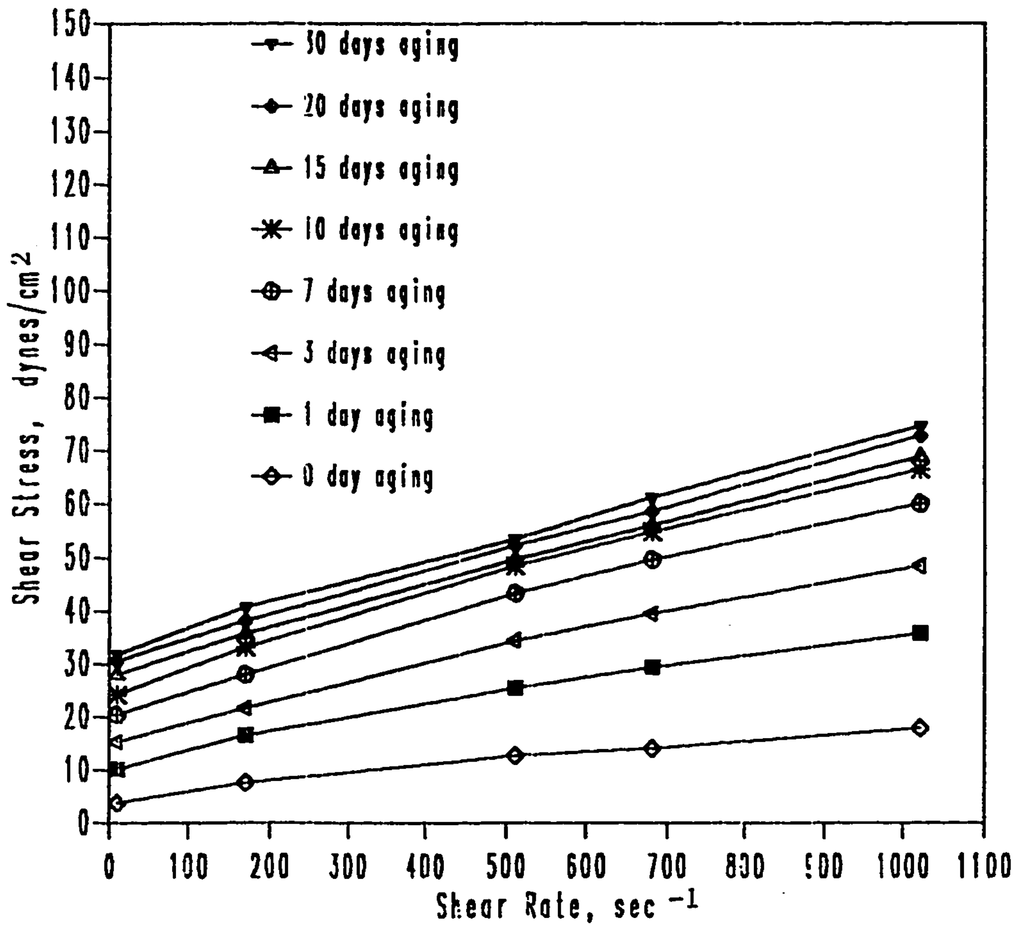


Fig.4.17: Shear Stress as a Function of Shear Rate for Different Aging Time at 302°F Temperature and 3000 psig Pressure.

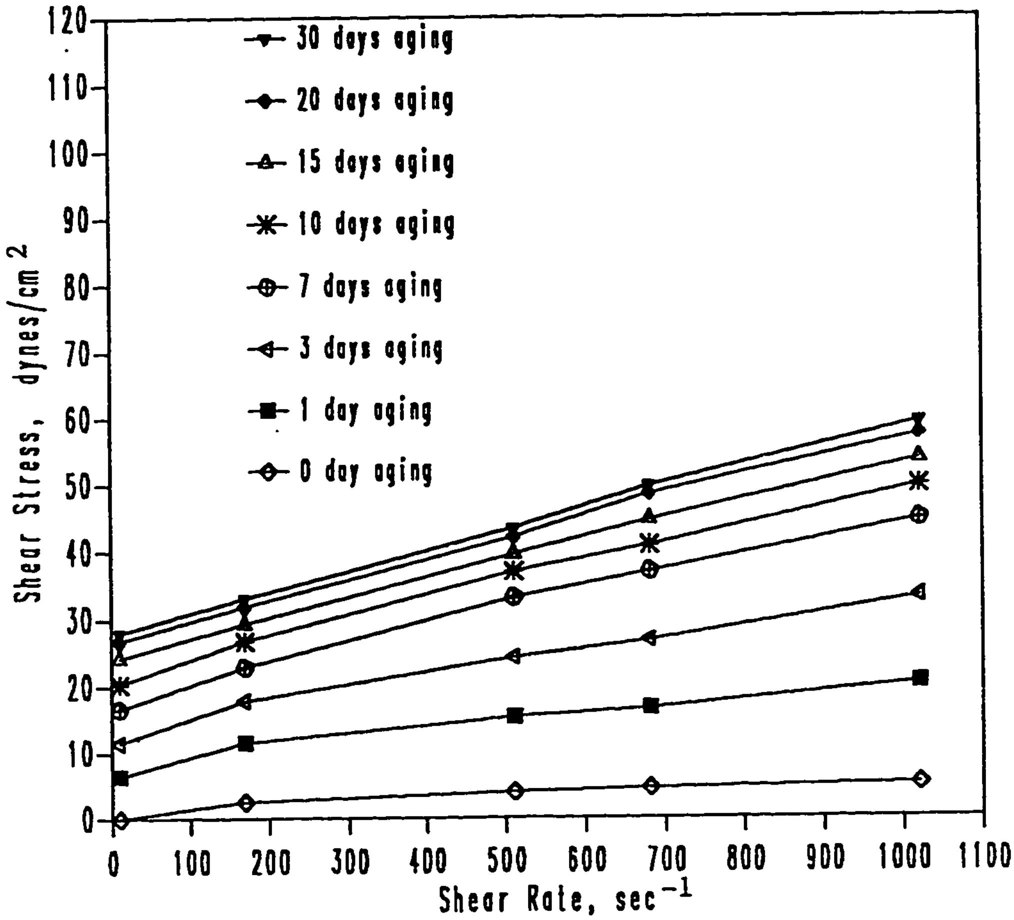


Fig.4.18: Shear Stress as a Function of Shear Rate for Different Aging Time at 392°F Temperature and 3000 psig Pressure.

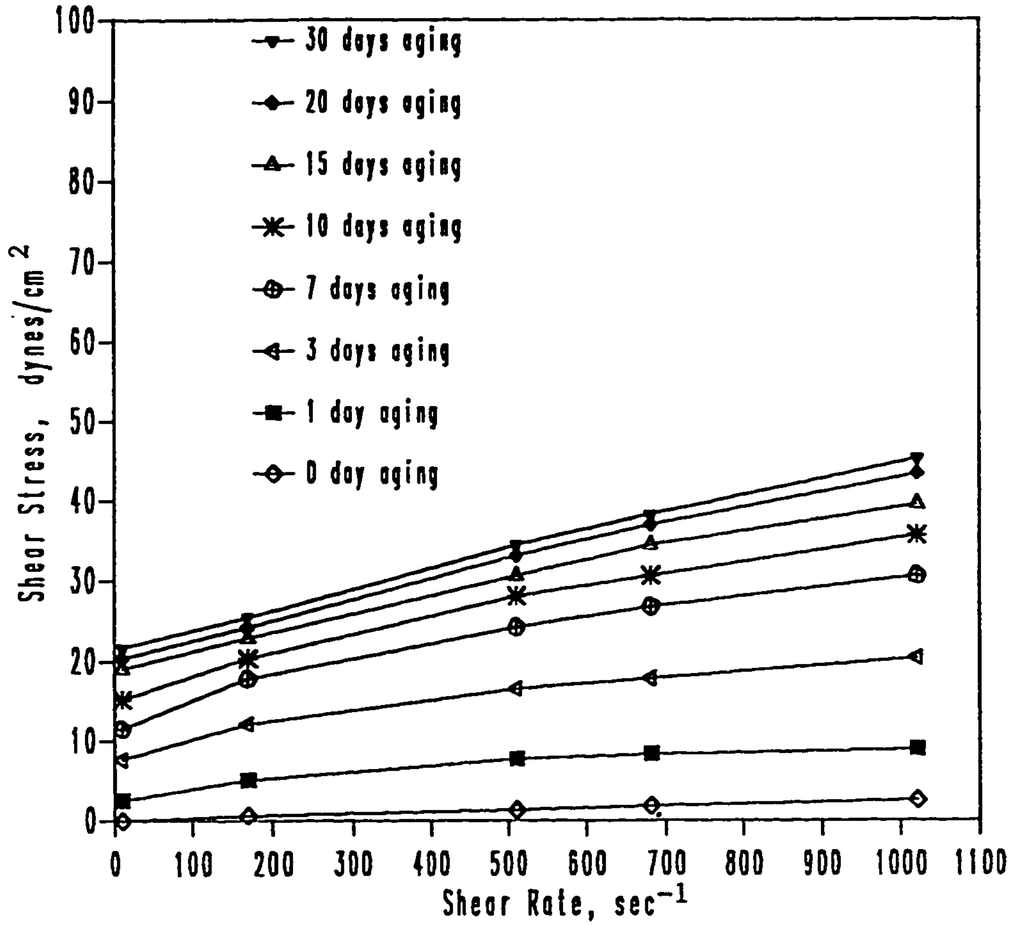


Fig.4.19: Shear Stress as a Function of Shear Rate for Different Aging Time at 490°F Temperature and 3000 psig Pressure.

dispersed the clay in suspension and higher the viscosity. Because, viscosity of the drilling fluid may increase due to the increase in density of the liquid phase, increase in particle numbers and due to the shape and size of the particles and also by interparticle forces. So as the particle number increases here, the viscosity of the drilling fluid increases. Since the rate of dispersion is more for first few days, the effects of aging is more initially and after that aging effect is diminishing with aging time.

As shown in Figures 4.3 through 4.5, the yield point and gel strength increase with aging time and aging effects are again diminishing with the increase in aging time. The explaination for this is that as the particle numbers increase, there is greater attractive and large interparticle forces and thus the yield point and gel strengths are also increased. The reason for diminishing effect of aging is the same as discussed before for the case of viscosity.

As shown in Figures 4.14 through 4.19, shear stress at a given shear rate increases with the aging time. This can be attributed again to the dispersion and flocculation effects of the drilling fluid. Viscosity is directly proportional to shear stress. As observed earlier that viscosity increases with aging time , cosequently shear stress also increases with aging time. The effect of aging on shear stress- shear rate relationship has good agreement with the result obtained by Annis [6] as shown in Figure 2.3. Annis [6] dynamically aged the mud for 24 and 48 hours at $300°F$ and observed that shear stress at a given shear rate increases with aging time. As he aged the mud only for 48 hours(maximum), there is no specific conclusion of his study. This study included the aging time of 0 day(no aging in the roller oven), 1 day, 3 days , 7 days, 10 days, 15 days, 20 days and 30 days in the roller oven and comes to a conclusion that aging effect on shear stress-shear rate is prominent initially and aging effects are diminishing with increase in aging time. The reason for this is that the rate of degree of dispersion and the degree of flocculation is greater initially and it is less as the aging continues.

The flow behavior of the drilling fluid has also been studied by calculating the value of the exponent of the power law index n and consistency index k. The value of the exponent of the power-law index n is calculated using the following equation,

$$n = 3.32 \log (\theta_{600} / \theta_{300}),$$

where the meaning of θ_{600} and θ_{300} has described earlier. The value of n as calculated by the above equation is shown in Table 4.1. The value of consistency index k is obtained using the equation,

$$k = \frac{\theta_{600}}{(1022)^n},$$

and is shown in Table 4.2.

Table 4.1: Power Law Index n as calculated from equation.

Aging (days)	Temperature					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
0	0.544	0.585	0.507	0.485	0.415	0.110
1	0.569	0.546	0.505	0.485	0.415	0.223
3	0.565	0.536	0.511	0.493	0.453	0.300
7	0.554	0.525	0.499	0.467	0.429	0.337
10	0.544	0.521	0.485	0.453	0.427	0.348
15	0.556	0.523	0.489	0.469	0.438	0.367
20	0.541	0.516	0.493	0.475	0.447	0.387
30	0.547	0.525	0.495	0.478	0.452	0.395
Average	0.553	0.535	0.498	0.476	0.435	0.308

Table 4.2: Consistency index k as calculated from equation.

Aging (days)	Temperature					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
0	2.058	1.195	1.026	0.620	0.288	0.220
1	2.349	2.117	1.695	1.239	1.150	1.903
3	2.745	2.704	2.106	1.591	1.436	2.551
7	3.182	3.186	2.610	2.356	2.283	2.962
10	3.558	3.414	3.098	2.872	2.580	3.202
15	3.382	3.469	3.142	2.670	2.574	3.107
20	3.842	3.725	3.182	2.703	2.591	2.967
30	3.744	3.572	3.200	2.717	2.586	2.931
Average	3.108	2.923	2.507	2.096	1.936	2.480

The values of n (< 1) indicates that the drilling fluid under study is pseudoplastic and this agrees with the results obtained by Block [17], where the n value is about 0.1 - 0.3 which indicates a high degree of pseudoplasticity.

This is well known before that temperature as well as aging have effects on the drilling fluid properties. It is also observed from this study that viscosity, yield point, gel strength and shear stress at a given shear rate decrease with temperature and increase with aging time. Many problems in drilling operation can be avoided or solved if the optimum value of these properties are maintained.

Viscosity materially influences penetration rate. Cuttings slip velocity is correlated better with yield point than any other parameters [32]. If the yield point is low, particle slip velocity is high and consequently, there will be problems in hole cleaning. Proper gel strength is required to keep the cuttings in suspension, and comparatively low gel strength is better for high penetration rate. It requires low pump pressure, and causes less pressure drop in the hole. Aging increases the drilling fluid properties. For an enlarged hole, increased viscosity and gel strength are better in order to clean the hole. But excessively high viscosity will decrease the penetration rate and high gel strength will cause low penetration rates, high swabbing and surge pressures, and needs high pump pressure.

Thus temperature and aging has some conflicting effects on drilling fluid properties. The conflicting rheological requirements will be minimized by using a shear-thinning mud , which sets to a gel strength which is sufficient to suspend cuttings when circulation is stopped, but breaks up quickly to a thin fluid when it is disturbed. Such drilling fluid will have low flow behavior index n.

CHAPTER 5

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based on the laboratory investigations and discussions presented in this study, the following conclusions are drawn:

1. Effective viscosity, plastic viscosity, yield point and gel strengths (10 sec. and 10 min.) decrease with the increase in temperature.

2. Shear stress at a given shear rate decreases with the increase in temperature and temperature effects are decreasing with the increase in temperature

3. Effective viscosity, plastic viscosity, yield point and gel strengths (10 sec. and 10 min.) increase with the increase in aging time.

4. Aging effects on effective viscosity, plastic viscosity, yield point and gel strengths (10 sec. and 10 min.) are decreasing with the increase in aging time.

5. Shear stress at a given shear rate increases with the increase in aging time and it is observed again that aging effects are decreasing with the increase in aging time.

6. The values of exponent of the power-law index (n) indicate that the flow of the fluids tested follow pseudoplastic model.

5.2 RECOMMENDATIONS

From the results of this study, the following recommendations are made for the extension of the present work:

1. Along with HTHP system, a measuring technique must be incorporated in order to facilitate measurement of filtration and corrosion rate as these two are also important properties of drilling fluid.

2. HTHP dynamic flow loop can be used for circulation rather than Baroid Roller Oven for better simulation of the bottom hole conditions.

3. The present work can be extended for different pressure to study the pressure effects on this drilling fluid.

NOMENCLATURE

NOMENCLATURE

SAPP	sodium - acid pyrophosphate
CMC	carboxy - methyl cellulose
μ_{Pmud}	plastic viscosity of mud
μ_{water}	viscosity of water
HTHP	high - temperature - high - pressure
SSMA	sulfonate styrene maleic anhydrite
PHPA	partially hydrated polyacrylamide
VSVA	vinylsulfonate - vinylamide
AMPS	acrylamido methyl propane sulfonate
AM	acrylamide
rpm	revolution per minute
KVA	kilo volt ampere
g	gram
μ_e	effective viscosity
μ_p	plastic viscosity
PV	plastic viscosity
YP	yield point
GS	gel strength
θ_{600}	dial reading at 600 rpm
θ_{300}	dial reading at 300 rpm
θ_3	dial reading at 3 rpm
n	power law index
k	viscosity constant / consistency index

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REFERENCES

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APPENDIX

Table A.1: Effective Viscosity (mPa.s) as a Function of Temperature for Different Aging Time at 3000 psig Pressure.

Aging (days)	Temperature					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
0	8.750	6.500	3.375	1.750	0.500	0.250
1	11.875	9.125	5.500	3.500	2.000	0.875
3	13.500	10.875	7.125	4.750	3.250	2.000
7	14.500	11.875	8.125	5.875	4.375	3.000
10	15.125	12.375	8.750	6.500	4.875	3.500
15	15.625	12.750	9.125	6.750	5.250	3.875
20	16.000	13.125	9.500	7.125	5.625	4.250
30	16.250	13.313	9.688	7.313	5.813	4.438

Table A.2: Plastic Viscosity (mPa.s) as a Function of Temperature for Different Aging Time at 3000 psig Pressure.

Aging (days)	Temperature					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
0	5.500	4.000	2.000	1.000	0.250	0.000
1	7.750	5.750	3.250	2.000	1.000	0.250
3	8.750	6.750	4.250	2.750	1.750	0.750
7	9.250	7.250	4.750	3.250	2.250	1.250
10	9.500	7.500	5.000	3.500	2.500	1.500
15	9.750	7.750	5.250	3.750	2.750	1.750
20	10.000	8.000	5.500	4.000	3.000	2.000
30	10.250	8.125	5.625	4.125	3.125	2.125

Table A.3: Yield Point (dPa) as a Function of Temperature for Different Aging Time at 3000 psig Pressure.

Aging (days)	Temperature					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
0	33.150	25.500	14.025	7.650	2.550	1.275
1	42.075	34.425	22.950	15.300	10.200	6.375
3	48.450	42.075	29.325	20.400	15.300	12.750
7	53.550	47.175	34.425	26.775	21.675	17.850
10	57.375	49.725	38.250	30.600	24.225	20.400
15	59.925	51.000	39.525	31.100	25.500	21.463
20	61.200	52.275	40.800	31.875	26.775	22.950
30	62.000	52.913	41.438	32.513	27.413	23.588

Table A.4: Initial Gel Strength(10 sec) as a Function of Temperature for Different Aging Time at 3000 psig Pressure.

Aging (days)	Temperature					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
0	20.400	14.025	6.375	2.550	0.000	0.000
1	28.050	21.675	14.025	10.200	5.100	2.550
3	31.875	26.775	19.125	14.025	10.200	6.375
7	36.975	31.875	24.225	19.125	15.300	10.200
10	40.800	35.700	28.050	22.950	19.125	14.025
15	43.350	38.250	30.600	25.500	21.675	16.575
20	45.900	40.800	33.150	28.050	24.225	19.125
30	47.175	42.075	34.425	29.325	25.500	20.400

Table A.5: 10 Minutes Gel Strength as a Function of Temperature for Different Aging Time at 3000 psig Pressure.

Aging (days)	Temperature					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
0	30.600	22.950	12.750	5.100	2.550	0.000
1	40.800	33.150	22.950	14.025	10.200	5.100
3	48.450	40.800	28.050	20.400	15.300	10.200
7	53.550	45.900	33.150	25.500	20.400	15.300
10	58.650	51.000	38.250	30.600	25.500	20.400
15	63.750	56.100	43.350	35.700	30.600	25.500
20	66.300	58.650	45.900	38.250	33.150	28.050
30	68.850	61.200	48.450	40.800	35.700	30.600

Table A.6: Experimental Data of Shear Rate - Shear Stress as a Function of Temperature for 0 Day Aging Time at 3000 psig Pressure.

Shear Rate sec^{-1}	Shear Stress, $dynes/cm^2$					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
1022	89.250	68.850	34.425	17.850	5.100	2.550
681	71.400	53.550	28.050	14.025	4.463	1.785
511	61.200	45.900	24.225	12.750	3.825	1.275
170	40.800	28.050	14.025	7.650	2.550	0.638
10	20.400	15.300	7.650	3.825	0.000	0.000

Table A.7: Experimental Data of Shear Rate - Shear Stress as a Function of Temperature for 1 Day Aging Time at 3000 psig Pressure.

Shear Rate sec^{-1}	Shear Stress, dynes/cm^2					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
1022	121.125	93.075	56.100	35.700	20.400	8.925
681	94.350	73.950	45.900	29.325	16.575	8.288
511	81.600	63.750	39.525	25.500	15.300	7.650
170	53.550	42.075	25.500	16.575	11.475	5.100
10	28.050	22.950	15.300	10.200	6.375	2.550

Table A.8: Experimental Data of Shear Rate - Shear Stress as a Function of Temperature for 3 Days Aging Time at 3000 psig Pressure.

Shear Rate sec^{-1}	Shear Stress, dynes/cm^2					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
1022	137.700	110.925	72.675	48.450	33.150	20.400
681	109.650	89.250	58.650	39.525	26.775	17.850
511	93.075	76.500	51.000	34.425	24.225	16.575
170	61.200	51.000	34.425	21.675	17.850	12.113
10	33.150	28.050	20.400	15.300	11.475	7.650

Table A.9: Experimental Data of Shear Rate - Shear Stress as a Function of Temperature for 7 Days Aging Time at 3000 psig Pressure.

Shear Rate sec^{-1}	Shear Stress, dynes/cm^2					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
1022	147.900	121.125	82.875	59.925	44.625	30.600
681	117.300	96.900	66.300	49.725	36.975	26.775
511	100.725	84.150	58.650	43.350	33.150	24.225
170	68.850	56.100	42.075	28.050	22.950	17.850
10	38.250	33.150	25.500	20.400	16.575	11.475

Table A.10: Experimental Data of Shear Rate - Shear Stress as a Function of Temperature for 10 Days Aging Time at 3000 psig Pressure.

Shear Rate sec^{-1}	Shear Stress, dynes/cm^2					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
1022	154.275	126.225	89.250	66.300	49.725	35.700
681	122.400	102.000	71.400	54.825	40.800	30.600
511	105.825	87.975	63.750	48.450	36.975	28.050
170	73.950	58.650	45.900	33.150	26.775	20.400
10	42.075	36.975	29.325	24.225	20.400	15.300

Table A.11: Experimental Data of Shear Rate - Shear Stress as a Function of Temperature for 15 Days Aging Time at 3000 psig Pressure.

Shear Rate sec^{-1}	Shear Stress, $dynes/cm^2$					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
1022	159.375	130.050	93.075	68.850	53.550	39.525
681	127.500	104.550	76.500	56.100	44.625	34.425
511	108.375	90.525	66.300	49.725	39.525	30.650
170	76.500	61.200	48.450	35.700	29.325	22.950
10	45.900	40.150	33.150	28.050	24.225	19.125

Table A.12: Experimental Data of Shear Rate - Shear Stress as a Function of Temperature for 20 Days Aging Time at 3000 psig Pressure.

Shear Rate sec^{-1}	Shear Stress, $dynes/cm^2$					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
1022	163.200	133.050	96.900	72.675	57.375	43.350
681	132.600	108.375	79.050	58.650	48.450	36.975
511	112.200	93.075	68.850	52.275	42.075	33.150
170	79.050	63.075	49.725	38.250	31.875	24.225
10	48.450	43.350	35.700	30.600	25.500	20.400

Table A.13: Experimental Data of Shear Rate - Shear Stress as a Function of Temperature for 30 Days Aging Time at 3000 psig Pressure.

Shear Rate sec^{-1}	Shear Stress, dynes/cm^2					
	77 °F	122 °F	212 °F	302 °F	392 °F	490 °F
1022	165.750	135.788	98.813	74.588	59.288	45.263
681	135.150	109.650	81.600	61.200	49.725	38.250
511	113.475	94.350	70.125	53.550	43.350	34.425
170	81.600	66.300	51.000	40.800	33.150	25.500
10	49.725	44.625	36.975	31.875	28.050	21.675